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Combined Approaches for Quantifying Groundwater-Surface Water Exchanges in Karst Watersheds

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Honors Capstone Project

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Introduction

Increasingly, groundwater and surface water are thought of as a single source [*Winter*, 1998]. This is due to the frequent groundwater-surface water exchanges that can occur on a varying spatial and temporal scale within a watershed. Geology and topography are two key factors in dictating the spatial frequency of these exchanges [*Winter*, 1999]. Understanding groundwater-surface water exchanges both temporally and spatially is critical to managing watersheds effectively. Quantifying these exchanges can be further complicated by the presence of karst geology within a watershed [*Lauber and Goldscheider*, 2014]. Large karst features can supply groundwater to surface waters with differing quantity and quality compared to groundwater sourced from the rest of the soil/geologic matrix.

In western watersheds variations in snowpack and geology cause spatial and temporal variability in annual streamflow due to the connected nature of the groundwater and surface water [*Tague et al.*, 2008]. The presence of karst geology combined with temporal variation in snowpack can potentially create even greater variability in streamflow conditions within karst watersheds. Methods for quantifying karst groundwater have centered on both spatially lumped and distributed models. Spatially lumped models utilize easily available data such as hydrographs and precipitation, while distributed models require detailed information about the matrix, conduits, and fractures within the aquifer [*Ghasemizadeh et al.*, 2012; *Jeelani et al.*, 2017; *Land and Timmons*, 2016]. These studies have required intensive data collection to simply model flows from karst conduit outlets or quantify the net groundwater contribution from combined matrix and karst conduit flowpaths. However, for effective watershed management in karst watersheds, individual components (both matrix and karst conduit) of the groundwater-surface water interactions occurring must be understood over time and space [*De Jong et al.*, 2008; *White*, 2002].

Studies in non-karst watersheds have used stream centric methods such as tracer studies, end-member mixing methods, and mass balance analysis to quantify groundwater inflows [*Batlle-Aguilar et al.*, 2014; *McCallum et al.*, 2012; *Miller et al.*, 2015], but these methods have not been applied to karst watersheds. To address the need for understanding the karst conduit and matrix influences in mountainous regions, a subset of these stream-centric methods were applied in a dominantly karst watershed with the objective of developing simpler approaches for quantifying groundwater-surface water exchanges at varying spatial and temporal scales. This objective was accomplished by first quantifying net groundwater-surface water exchanges at a reach and sub-reach scale and then by quantifying karst and matrix inflows and groundwater losses at the sub-reach scale.

Study Site

The Logan River watershed is located in the Bear River Range of northern Utah with the headwaters originating in southeastern Idaho. The area of interest is the mountainous portion of the watershed due to its karst geology (Figure 1a). Most if not all of the geologic layers in the canyon contain karst features, but are most developed in the Garden City Formation and

Laketown Dolomite. The Swan Peak Quartzite acts as an impermeable boundary between the two (Figure 1b).

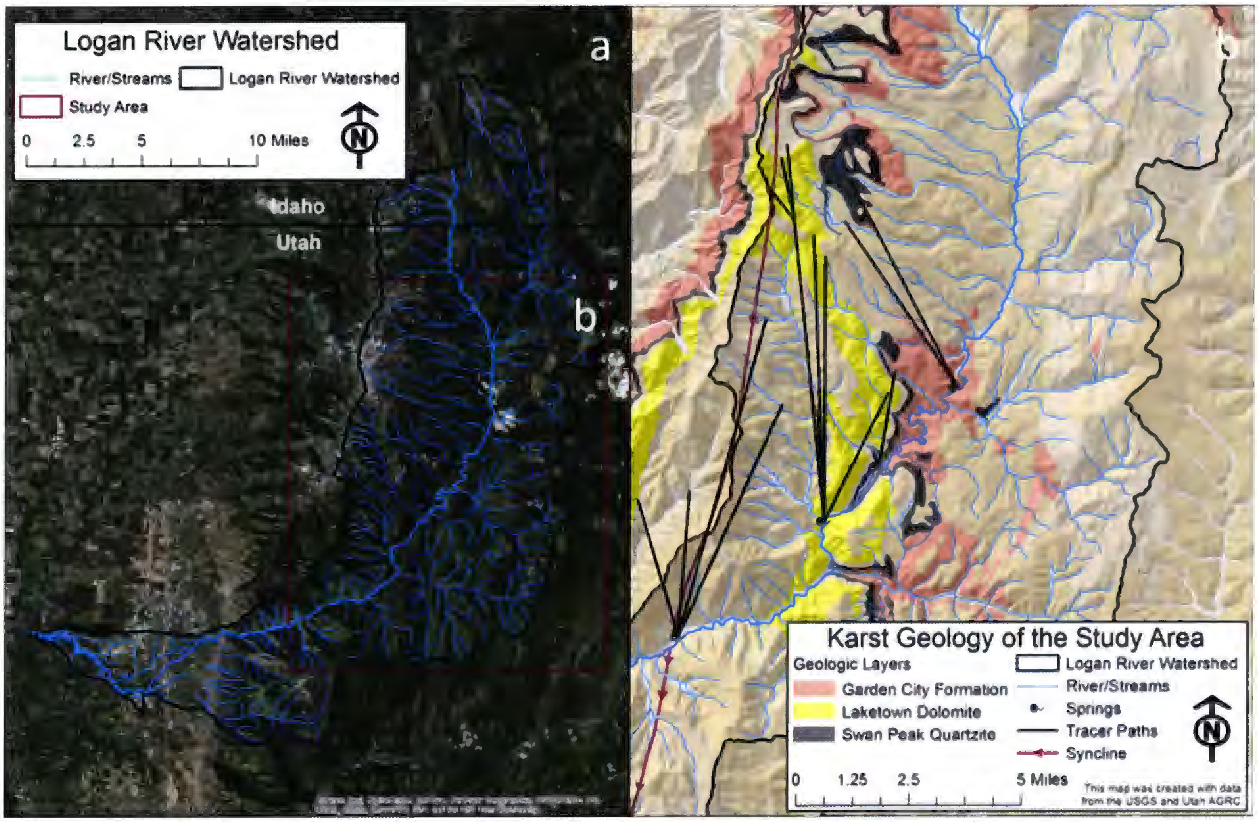

Figure 1. (a) The Logan River Watershed and study area, (b) karst geology of the study area.

The river itself is a major source of agriculture water for communities within Cache Valley, Utah. Dewitt Springs along with Wood Camp Spring and Ricks Spring are three karst springs that contribute significantly to instream flow of the Logan River. The syncline (Figure 1b) parallels the Logan River for much of the mountainous portion of the watershed before intersecting the river a few miles from the canyon mouth. The intersection of the syncline with the river corresponds with Dewitt Springs. Dewitt Springs is additionally used as the primary drinking water source for Logan City, Utah. Previous work has delineated groundwater drainage areas and approximate travel times for the three major karst springs in the watershed and have shown intra-basin connectivity (Figure 1b) [*Spangler*, 2001].

Data Collection

Measurements of flow, temperature, specific conductivity, pH, DO concentration, % DO saturation, stage, and ion concentrations were made over the course of the project. Data collection efforts were focused at a reach and sub-reach scale. At the reach scale, data were collected continuously, while at the sub-reach scale point sampling events were completed.

Collection Methods

Flow measurements were made using the velocity-area or dilution gauging method [*Rantz*, 1982]. Under typical flow conditions, velocity measurements were made using an YSI FlowTracker handheld ADV. At high flows when the Logan River became un-wadeable, measurements were made using a Marsh McBirney Flo-Mate 2000 Flow Meter on a weighted line from a truck with a boom and reel or from a bridge cart. While this high flow measurement method was effective, measurements should be regarded with a greater uncertainty because of the inherent difficulties accompanying higher flows, e.g., accurately determining water depth and maintaining a constant position for velocity measurements. Due to the low flow of Tony Grove Creek, White Pine Creek, and Little Bear Creek, discharge measurements of those tributaries were frequently conducted by dilution gauging.

Stage measurements were made by collecting pressure data using Campbell Scientific CS451 pressure transducers, non-vented In-Situ AquaTroll 200 pressure transducers, and YSI 600 LS Sondes. In-Situ BaroTrolls were also deployed to collect barometric pressure data for the depth correction of the AquaTroll data. Pressure/depth measurements were recorded every 15 minutes and converted to stage and/or water surface elevation by relating the measured water depth to a surveyed benchmark at each site.

Measurements of temperature, specific conductivity, pH, DO concentration, and % DO saturation were made using YSI 69020 V2 sondes, YSI EXO multiple parameter sonde, or YSI 600 LS sondes. Ion concentrations were measured by immediately filtering samples through a 0.45 μm nylon filter into acid-washed LDPE bottles. Samples analyzed for Cl^-, SO_4^{2-}, PO_4^{3-}, NO_3^-, and F^- were frozen and samples analyzed for Na^+, Mg^{2+}, Ca^{2+}, K^+, and NH_4^- were acidified with nitric acid. A complete description of the analytical methods used for processing all samples is provided within *Gabor et al.* [2017].

Reach Scale Measurements

Reach scale sites consist of a total of 9 gauging stations including: two Logan River iUTAH GAMUT sites, Franklin Basin and Tony Grove; two main-stem gauging sites, Dewitt Springs Campground and Wood Camp; three perennial streams, Beaver Creek, Temple Fork, and Right Hand Fork; and two major karst springs, Ricks Spring and Dewitt Springs (Figure 2). At each site measurements of water depth were made every fifteen minutes and later converted to flows using a rating curve that was developed for each site.

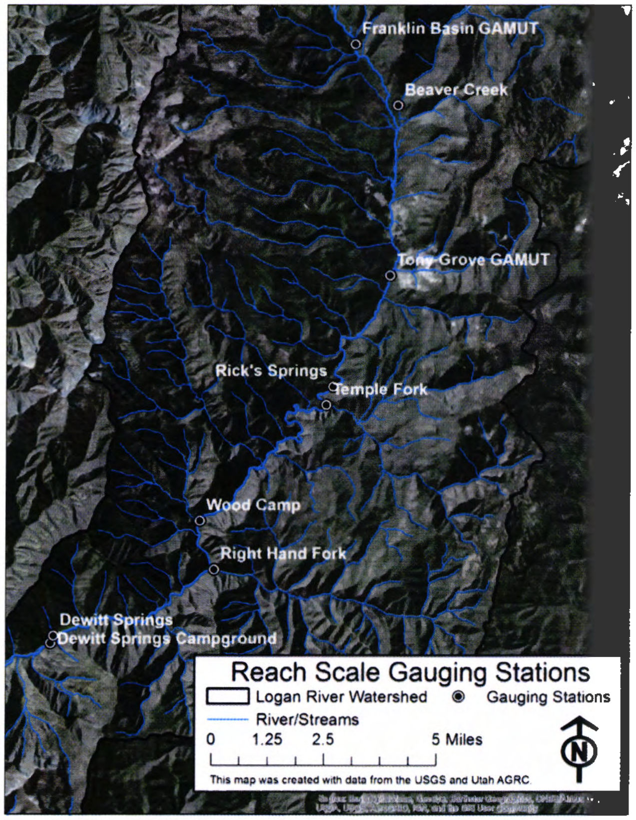

Figure 2. Reach scale gauging stations.

The iUTAH GAMUT sites were established as part of the greater iUTAH project (NSF EPSCoR grant IIA 1208732). Working in conjunction with iUTAH, the Franklin Basin and Tony Grove GAMUT stations were maintained and provided accurate discharge data. Data collection at Tony Grove GAMUT began in 2014 and 2015 for the Franklin Basin GAMUT; however, only data from June of 2015 to July of 2017 were used in this project.

The other seven gauging stations in the study area were established and maintained as part of this project. Data collection began in June of 2015 at these sites with the exception of Wood Camp where data collection began May of 2016.

Sub-reach Scale Measurements

In June of 2014 flow, temperature, and specific conductivity were measured at cross sections spaced incrementally along the Logan River between Tony Grove GAMUT and Dewitt Springs Campground over a two day period. The measurements were repeated in August and December of 2014. In June 2015 flow, temperature, and specific conductivity were measured and ion samples were collected at cross sections between Franklin Basin GAMUT and Dewitt Springs Campground in a two day sampling event (Figure 3a). The measurements and sample collection was repeated in August of 2015 and pH, DO concentration, and % DO saturation were additionally measured. In February of 2016 ion samples were collected for Rick's Spring, Temple Fork Spring, Pullout Spring, Logan Cave Spring, Wood Camp Spring, and Dewitt Springs. Flow, temperature, specific conductivity, and pH were measured and ion samples were collected in May 2016 at a lower spatial resolution due to high flow conditions during spring runoff. A more comprehensive ion sampling of springs within the watershed was conducted in July of 2017 (Figure 3b).

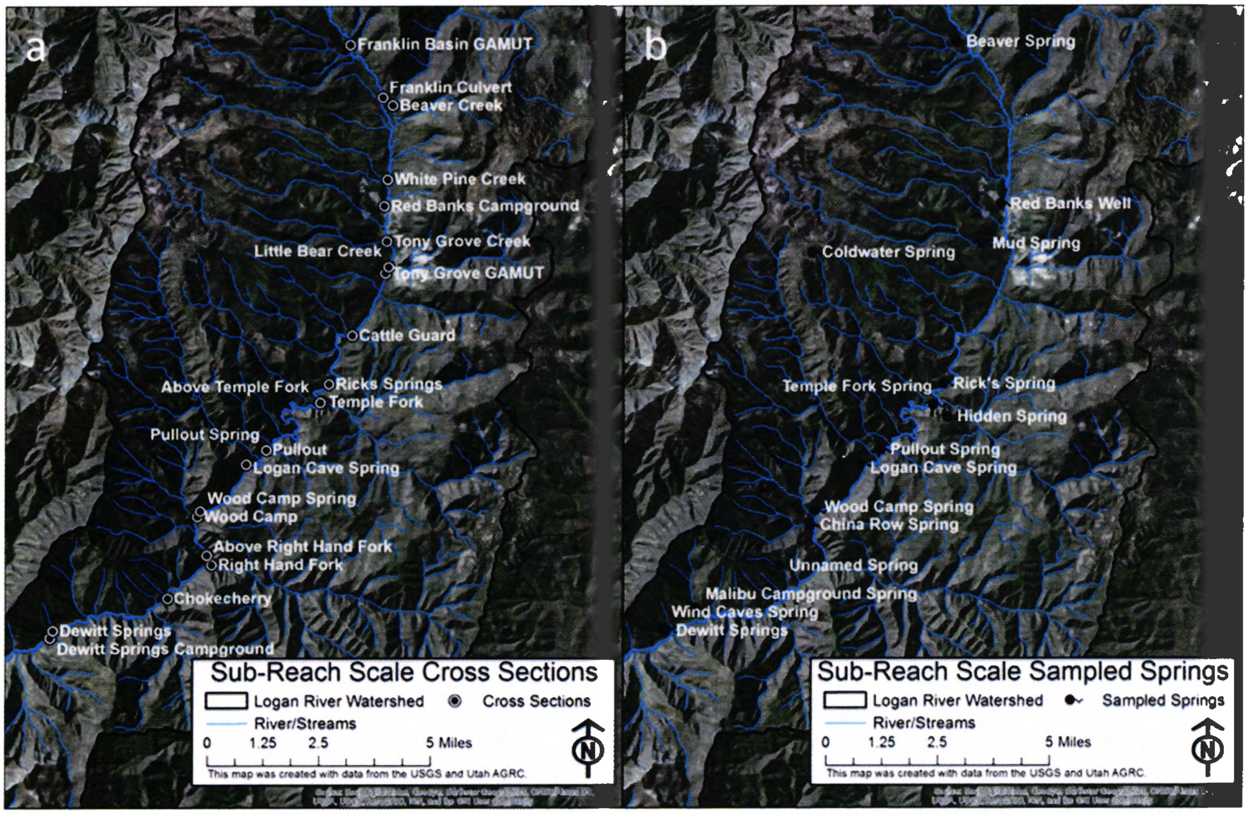

Figure 3. (a) Sub-reach scale gauging cross sections. (b) Sampled springs.

Analysis

Reach Scale Analysis

The 15-minute data collected at the 9 gauging stations, Franklin Basin GAMUT, Beaver Creek, Tony Grove GAMUT, Rick's Spring, Temple Fork, Wood Camp, Right Hand Fork, Dewitt Springs, and Dewitt Springs Campground from 2015 through 2017 were averaged over a 24-hour period to determine and average daily flow.

Using the simple flow balance shown in Eqn. 1, the net change in streamflow due to groundwater discharge to the stream or loss of streamflow to groundwater was quantified.

$$Q_2 - Q_{trib} - Q_1 = Q_{net} \qquad \text{Eqn. 1}$$

Where Q_2 is the flow at the downstream gauging station ($m^3 s^{-1}$), Q_{trib} is the flow of any tributaries within the reach ($m^3 s^{-1}$), Q_1 is the flow at the upstream gauging station ($m^3 s^{-1}$), and Q_{net} is the net change in streamflow ($m^3 s^{-1}$) due to groundwater-surface water interactions (the sum of the karst and matrix inflows and the water lost from the river to the aquifer).

The net groundwater-surface water exchange was also calculated with the influence of Ricks Spring, and Dewitt Springs removed (Eqn. 2). Because of the inability to gauge Wood Camp Spring, the influence of this spring on groundwater-surface water exchange could not be determined.

$$Q_2 - Q_{trib} - Q_{spring} - Q_1 = Q_{net} \qquad \text{Eqn. 2}$$

Where Q_{spring} ($m^3\ s^{-1}$) is the flow from any karst springs within the reach. The percent change relative to upstream flow was also calculated for both Eqn. 1 and Eqn. 2 using Eqn. 3.

$$\%Q_{net} = \frac{Q_{net}}{Q_1} \times 100 \qquad \text{Eqn. 3}$$

This analysis is based on four assumptions:

1. All major tributaries contributing to main-stem flow are gauged.
2. Un-gauged tributaries do not account for a statistically significant portion of the main-stem flow.
3. Using Eqn. 1, it is assumed that any change in flow within a reach, with the exception of gauged tributaries, is due to groundwater-surface water exchange (this means that springs are considered a source of karst groundwater discharge).
4. Using Eqn. 2, it is assumed that the change in flow within a reach is due to matrix discharge to the river or losses from the river because the discharge from the major karst springs is removed.

Sub-reach Scale Analysis

At the sub-reach scale a flow balance and a mass balance were used to determine both the net and gross groundwater-surface water exchanges occurring between cross sections. Net flow balances were similar to those completed at the reach scale and implemented Eqn. 1.

Mass Balance:

New flow and mass balance equations that accounted for the flow and ion concentrations of karst inflow, matrix inflow, surface water loss, tributaries, and the upstream and downstream cross sections were developed (Eqn. 4-5).

$$Q_2 + Q_{loss} - Q_{trib} - Q_{matrix} - Q_{karst} - Q_1 = 0 \qquad \text{Eqn. 4}$$

$$Q_2C_2 + Q_{loss}C_{loss} - Q_{trib}C_{trib} - Q_{matrix}C_{matrix} - Q_{karst}C_{karst} - Q_1C_1 = 0 \qquad \text{Eqn. 5}$$

Where Q_{matrix} is the flow gained from matrix flowpaths ($m^3\ s^{-1}$), Q_{karst} is the flow gained from karst conduits ($m^3\ s^{-1}$), Q_{loss} is the groundwater loss ($m^3\ s^{-1}$), and C is the ion concentration of each of the respective flows ($mg\ L^{-1}$).

During the sub-reach sampling events only Q_2, C_2, Q_1, C_1, Q_{trib}, and C_{trib} were measured. Values for Q_{loss}, C_{loss}, Q_{matrix}, C_{matrix}, Q_{karst}, and C_{karst} could not be directly sampled due to their diffuse nature, potential mixing with river water at inlets/outlets, and an absence of groundwater wells in

Logan Canyon. However, a series of assumptions were used that produces a solvable form of Eqns. 4 and 5:

1. The ion concentration of the streamflow loss to groundwater, C_{loss}, is assumed to be the ion concentration measured at the upstream or downstream cross section, C_1 or C_2. This assumption produces two alternatives one where river outflow occurs before groundwater inflow (OI), or a condition where groundwater inflow occurs before river outflow (IO).

2. Values for C_{karst} are assumed to be greater than zero and less than or equal to the highest sampled ion concentration at a karst spring during any of the sub-reach scale sampling events. In the analysis, values for C_{karst} were set to the minimum, maximum, and average observed ion concentrations sampled at the karst springs.

3. The ion concentration of C_{matrix} is assumed to be greater than C_{karst} and less than a maximum ion concentration set arbitrarily high, but based on sampled ion concentrations of springs and the only well in the canyon at Red Banks Campground.

4. Values for Q_{loss} were assumed to range from 0 to 1 m^3s^{-1} (approximately 15% the maximum observed streamflow in June 2015 and 30% the maximum observed in August 2015).

Using the first assumption Eqn. 5 can be re-written as:

$$Q_2C_2 + Q_{loss}C_{1,2} - Q_{trib}C_{trib} - Q_{matrix}C_{matrix} - Q_{karst}C_{karst} - Q_1C_1 = 0 \qquad \text{Eqn. 6}$$

A range of possible values for Q_{karst} and Q_{matrix} were determined by solving Eqn. 4 and 6 for a full factorial combination of the assumed values for C_{karst}, C_{matrix}, and Q_{loss} under both scenarios given in the first assumption, IO or OI. The ranges and increment that C_{karst}, C_{matrix}, and Q_{loss} were evaluated at are given in Table 1.

Table 1. Ranges for assumed values of C_{karst}, C_{matrix}, and Q_{loss}.

C_{karst}	Minimum	Maximum	Average
Na^+	0.34 mg L^{-1}	2.9 mg L^{-1}	1.5 mg L^{-1}
Cl^-	0.78 mg L^{-1}	5.39 mg L^{-1}	1.82 mg L^{-1}
Mg^{2+}	2.26 mg L^{-1}	19.82 mg L^{-1}	13.77 mg L^{-1}
Ca^{2+}	13.27 mg L^{-1}	56.5 mg L^{-1}	39.09 mg L^{-1}
SO_4^{2-}	0.89 mg L^{-1}	7.49 mg L^{-1}	2.85 mg L^{-1}
C_{matrix}	**Lower Bound**	**Upper Bound**	**Increment**
Na^+	3.0 mg L^{-1}	50.0 mg L^{-1}	0.1 mg L^{-1}
Cl^-	5.4 mg L^{-1}	50.0 mg L^{-1}	0.1 mg L^{-1}
Mg^{2+}	20.0 mg L^{-1}	200.0 mg L^{-1}	0.5 mg L^{-1}
Ca^{2+}	57.0 mg L^{-1}	200.0 mg L^{-1}	0.5 mg L^{-1}
SO_4^{2-}	7.5 mg L^{-1}	50.0 mg L^{-1}	0.1 mg L^{-1}
Q_{loss}	**Lower Bound**	**Upper Bound**	**Increment**
	0.00 m^3 s^{-1}	1.00 m^3 s^{-1}	0.02 m^3 s^{-1}

Results

Reach Scale Results

Rating curves for relating flow to stage were established at each of the 9 gauging stations (Figures A1-A9). Because of an inability to measure discharge during some peak flow events and the uncertainty of high flow measurements, the rating curves for each site were capped at the highest measured flow/stage and any stage recorded above that point was not considered. Flows were sampled across a range of stages at each site and a minimum of eight measurements were used to establish rating curves with R^2 values greater than 0.96 with the exception of Dewitt Springs which had an R^2 of 0.45. Because Dewitt Springs is the primary drinking water source for Logan City who has a water right allocation for 35 cfs, the spring is captured in a spring box and the outfall for the residual flow has an automated level control which creates variable channel hydraulics. The residual flow from the spring is gauged as it is diverted into the Logan River; however, the level control on the spring box creates a poor goodness of fit for the rating curve.

A third major karst spring, Wood Camp Spring, exists just upstream of the Wood Camp gauge. This spring has two outlets, the smaller of which is submerged for most of the year and the larger of which discharges from an approximately 20’ x 30’ area of fractured rock adjacent to the Logan River. Because of the two outlets, the spring is ungauged. Differential gauging above and below the spring has shown the spring accounts for an approximate 10-40% increase in river flow depending on the time of year.

Examination of the hydrographs for each of the main-stem sites within the study area shows that the Logan River is a net gaining river from the upstream boundary at Franklin Basin GAMUT to the downstream boundary at Dewitt Springs Campground (Figure 4). Gaps in the hydrographs in the spring of 2017 are periods of time for which the maximum measured flow used in the rating curve development was exceeded.

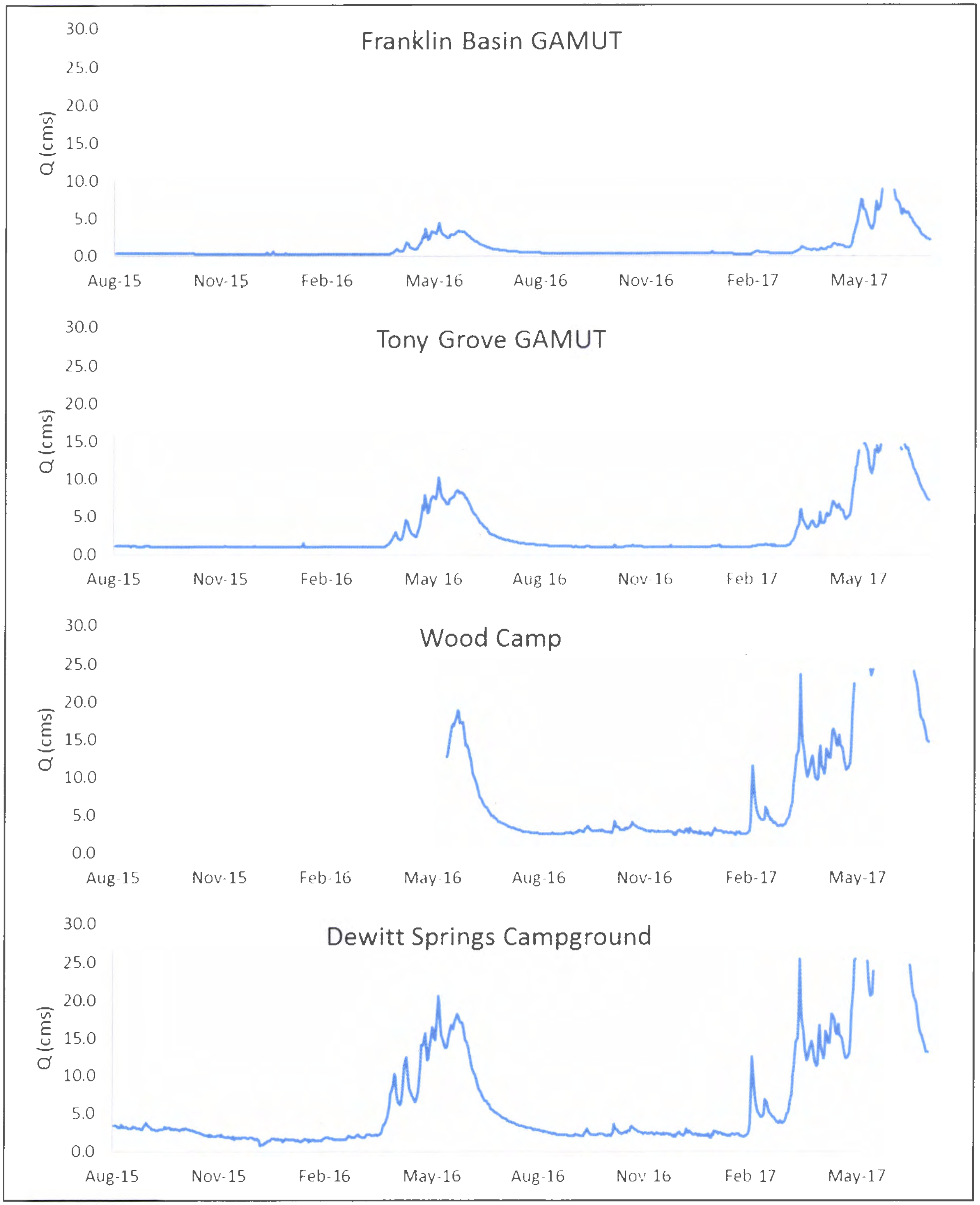

Figure 4. Measured flow at main-stem gauges.

Because the Wood Camp gauging station was not established until May 2016, the reach scale analysis using Eqns. 1, 2 and 3 was conducted from the Tony Grove GAMUT to Dewitt Springs Campground, from Tony Grove GAMUT to Wood Camp, and Wood Camp to Dewitt Springs Campground (Figure 5). Results from Eqn. 1 include the flow from gauged karst springs in the determined net change in flow and Eqn. 2 subtracts the flow from gauged karst springs from the net change in flow. Between Franklin Basin GAMUT and Tony Grove GAMUT instream flow is always increasing with the greatest variability in winter and spring months. Flow in the Tony Grove GAMUT to Dewitt Springs Campground reach sees a significant increase in the spring follow by a downward trend toward a loss of flow through the summer and winter. From Tony Grove GAMUT to Wood Camp flow is always increasing with the greatest increases occurring during the spring. From Wood Camp to Dewitt Springs Campground instream flow is almost always lost with a slight increase in flow during the spring. Calculation of the average and standard deviation of the net change in flow shows that between Franklin Basin GAMUT and Wood Camp the Logan River is a dominantly gaining river while between Wood Camp and Dewitt Springs Campground the river predominantly experiences a net loss with periodical small net gains (Table 2).

Table 2. Average and standard deviation of the net change in flow within gauged reaches.

	Eqn. 1		Eqn. 2	
	Average (%)	Std Dev (%)	Average (%)	Std Dev (%)
Franklin Basin GAMUT -Tony Grove GAMUT	190	± 55	191	± 55
Tony Grove GAMUT - Dewitt Springs Campground	71	± 70	31	± 71
Tony Grove GAMUT - Wood Camp	116	± 68	98	± 68
Wood Camp - Dewitt Springs Campground	-13	± 15	-21	± 18

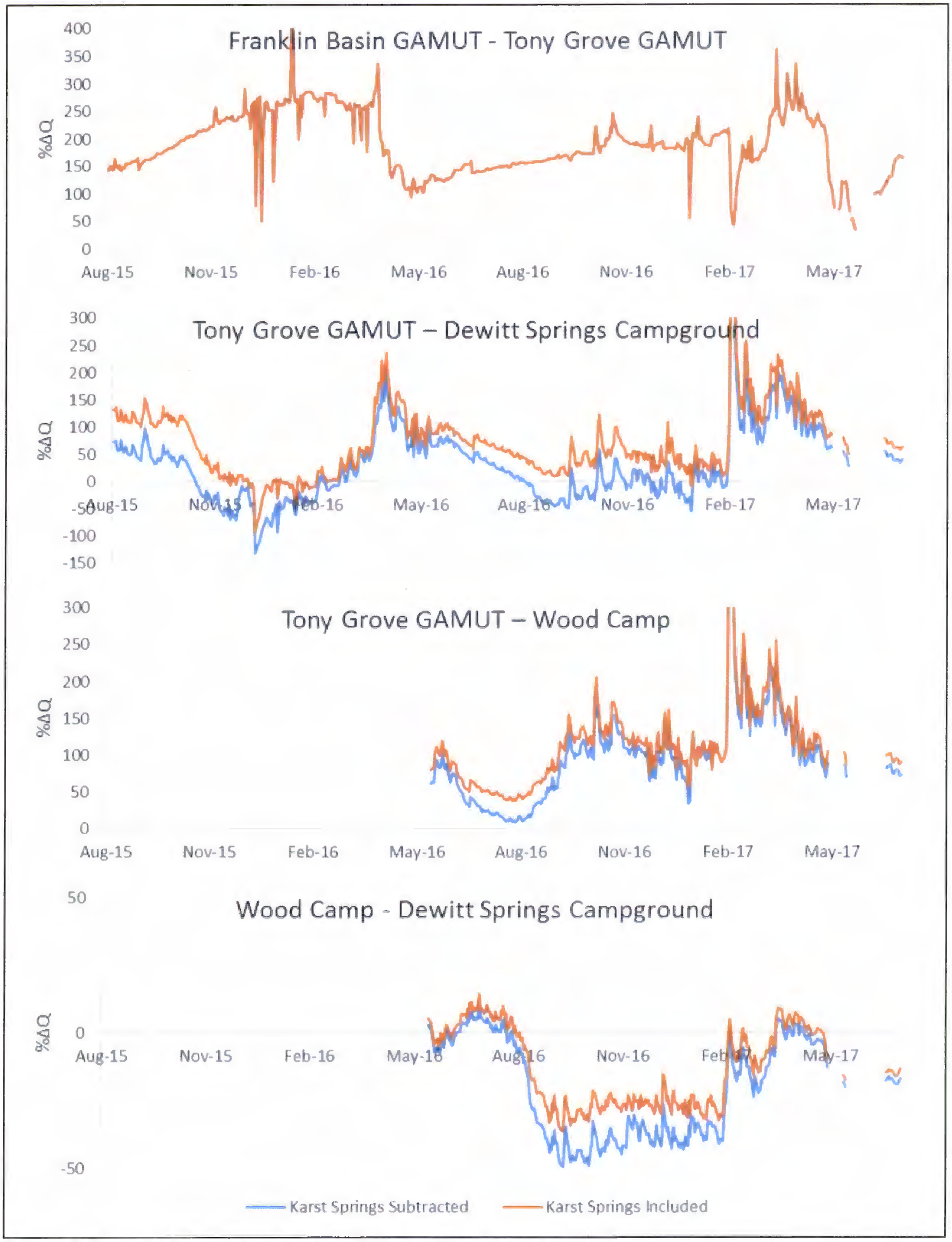

Figure 5. Percent change in flow between gauging stations.

Sub-reach Scale Results

The flow data collected during the sampling events in June, August, and December 2014; June and August 2015; and May 2016 (Tables B1-B9) were used to determine Q_{net} using Eqn. 1 for each sub-reach (Figure 6).

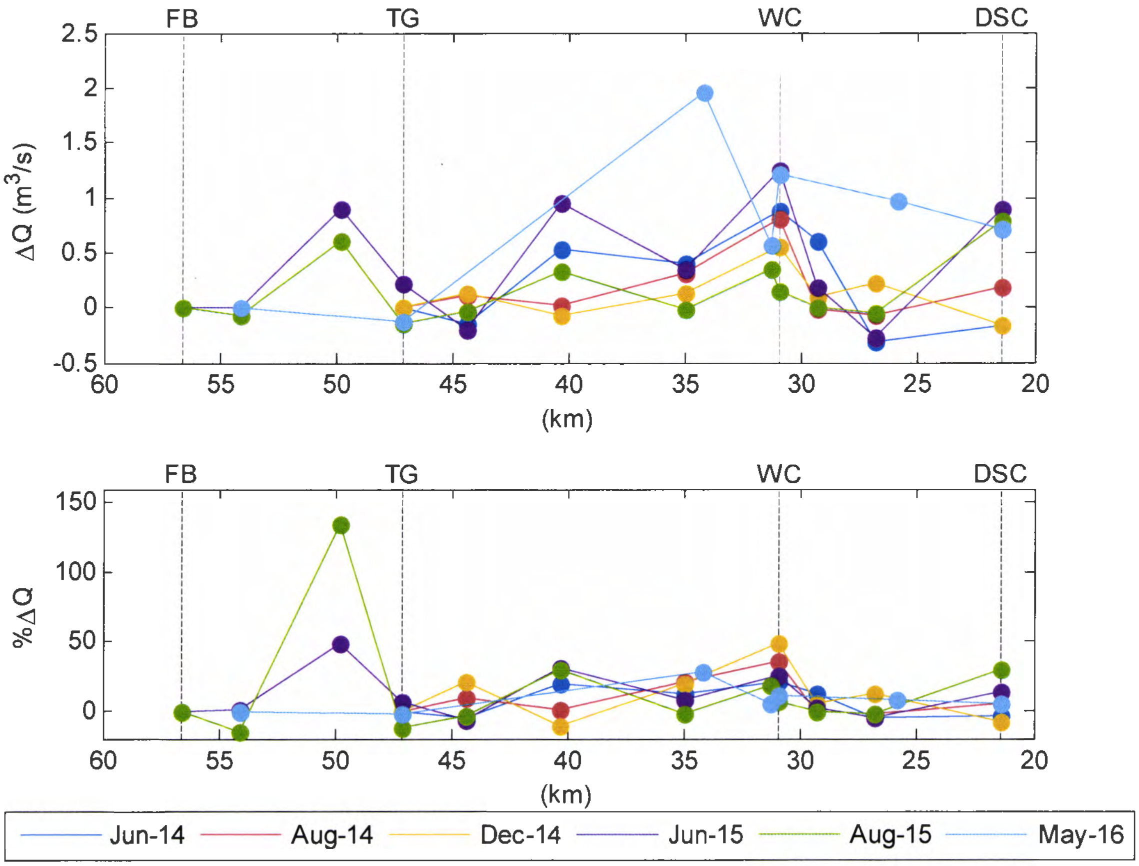

Figure 6. Q_{net} for flow data collected between Jun-14 and May 2016.

A total of 84 ion samples were collected at 40 different springs, tributaries, and main stem sites (Tables C1-C10). The samples of the springs and a single well were used to establish the bounds for assumptions 2 and 3 utilized in the mass balance analysis (Figure 7).

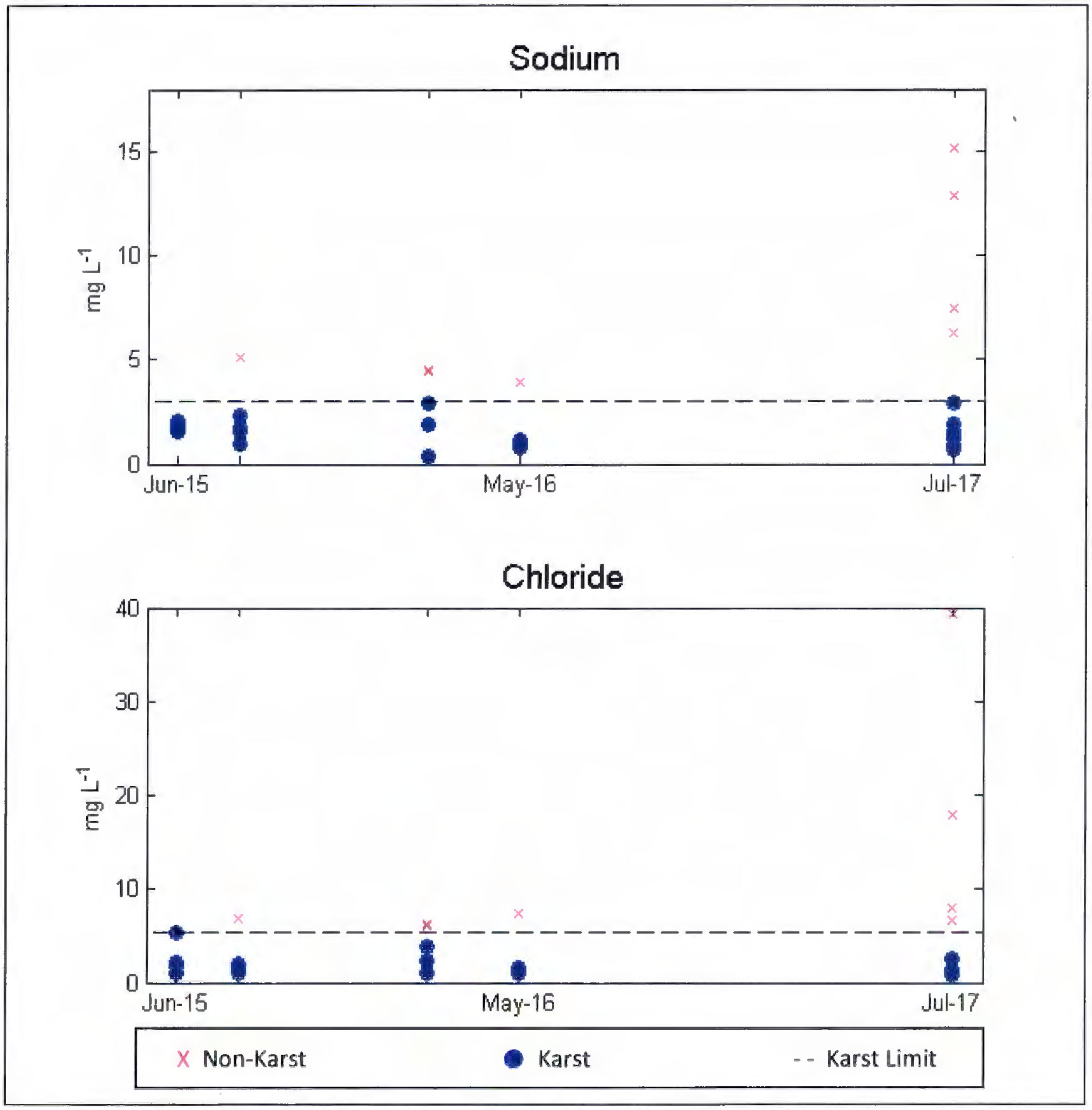

Figure 7. Concentrations of springs shown as karst or non-karst for Sodium and Chloride.

Using the flow measurements and ion samples collected in June and August of 2015, Eqn. 1 was used to determine Q_{net} and Eqns. 4 and 6 were used to determine, Q_{karst}, Q_{matrix}, and Q_{loss}. For the June data the net flow analysis (Eqn 1) was completed for four sub-reaches and for August there were 7 sub-reaches (Figure 8). The variable length of the sub-reaches is based on the river distance at which a significant changes in ion concentrations were measured in the main channel (which was important for the next set of analyses). The calculated percent net change in flow occurring in each sub-reach using Eqn. 1 for the June and August 2015 data (Table 3) show that in June, all reaches experience a net postive gain. This is expected given the data was collected

2, 4, 6, and 7 result in a net gain between Franklin Basin GAMUT and Dewitt Springs Campground.

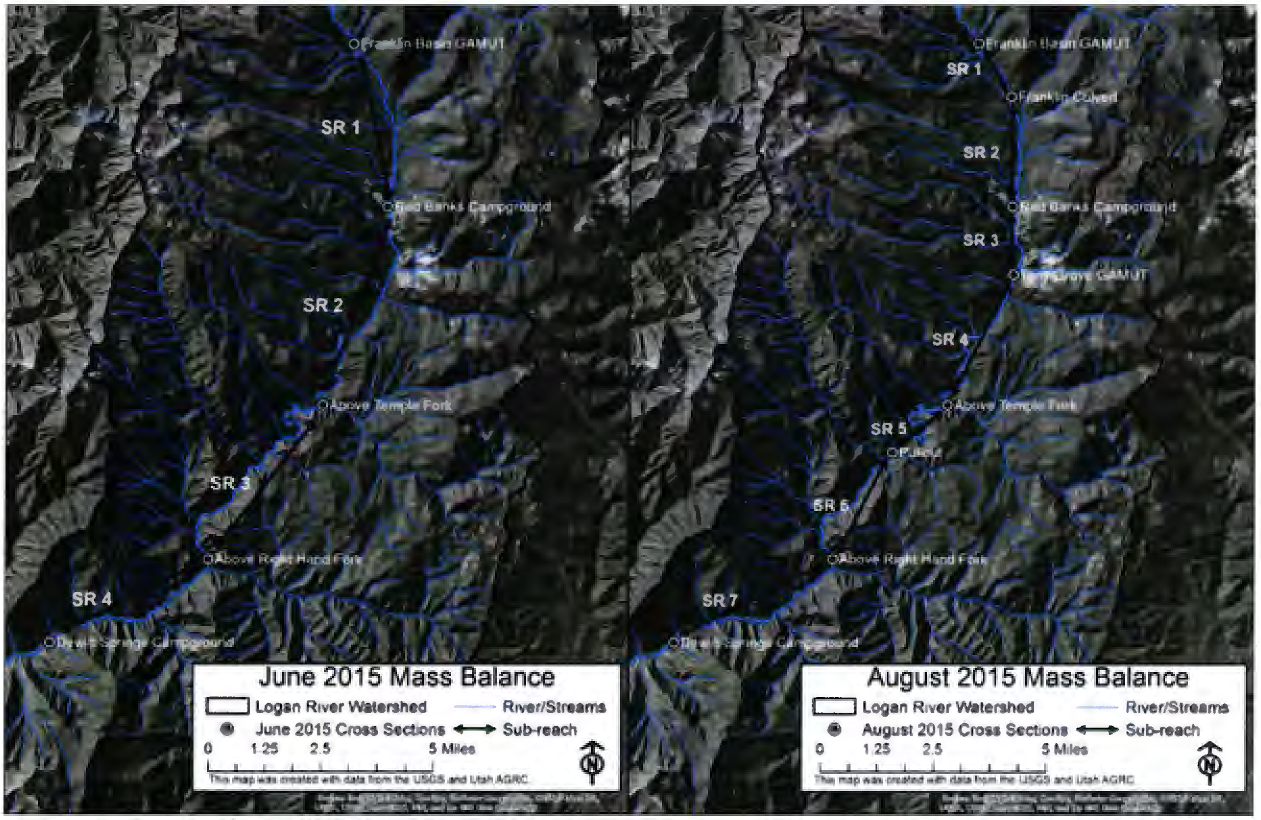

Figure 8. June and August 2015 sub-reaches.

Table 3. Percent net change in flow for June and August 2015 sub-reaches.

Jun-15		Aug-15	
Sub-reach	$\%Q_{net}$	Sub-reach	$\%Q_{net}$
SR 1	49.8	SR 1	-14.3
SR 2	32.2	SR 2	135.2
SR 3	43.6	SR 3	-12.4
SR 4	9.8	SR 4	28.0
		SR 5	-1.3
		SR 6	26.4
		SR 7	29.7

For the mass balance analyis Sodium, Chloride, Sulfate, Magnesium, and Calcium were used to conduct the analysis. The above ions reperesent the subset of all ions sampled for which data was available at each site and were above detection limits. Results from the mass balance analysis using Eqns. 5 and 6 for the Sodium and Chloride ion samples (Figure 9) show the percent change in flow relative to the flow of the upstream main-stem cross section. No values could be calculated for Chloride in June for SR 3 using the parameters presented in Table 1. Results are similar for all ions used.

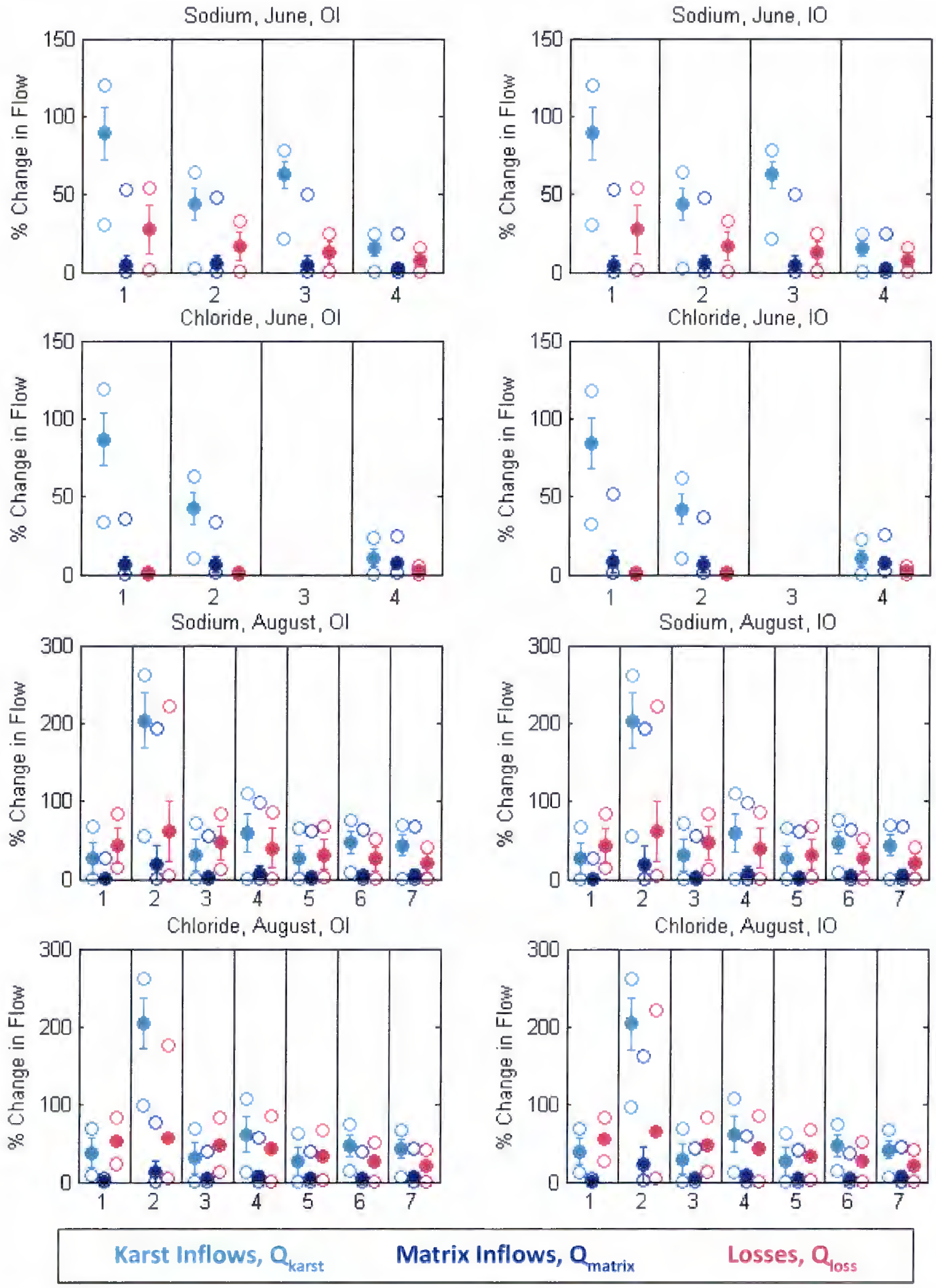

Figure 9. Percent change in flow in June and August under the IO and OI conditions for Q_{karst}, Q_{matrix}, and Q_{loss} across each sub-reach for Sodium and Chloride. Solid dots represent the average, hollow dots the minimum and maximum, and brackets the standard deviation.

Results of the analysis are presented as an average, standard deviation, maximum, and minimum based on all solutions given the ranges of possible values for C_{karst}, C_{matrix}, and Q_{loss} used within Eqns. 4 and 6. Using Chloride as a tracer, no solutions were calculated for sub-reach 3 in June 2015.

Table 4 shows the overall mean and compostite standard deviaion of the percent change in flow for Q_{matrix}, Q_{loss}, and Q_{karst} based on the analyses using all ions and the IO and OI condition. The percent net change in flow across each reach, Q_{net}, found as part of the flow balance analysis is also included.

Table 4. Comparison of Q_{matrix}, Q_{loss}, Q_{karst}, and Q_{net}.

Jun-15					Aug-15				
Sub-reach	%Q_{matrix}	%Q_{loss}	%Q_{karst}	%Q_{net}	Sub-reach	%Q_{matrix}	%Q_{loss}	%Q_{karst}	%Q_{net}
SR 1	7 ± 10	28 ± 16	71 ± 18	50	**SR 1**	4 ± 6	51 ± 21	33 ± 19	-14
SR 2	6 ± 6	17 ± 9	43 ± 10	32	**SR 2**	35 ± 43	72 ± 47	173 ± 40	135
SR 3	7 ± 8	12 ± 7	50 ± 10	45	**SR 3**	5 ± 7	49 ± 21	32 ± 20	-12
SR 4	4 ± 4	8 ± 4	13 ± 5	10	**SR 4**	9 ± 11	43 ± 25	60 ± 24	27
					SR 5	4 ± 5	35 ± 19	29 ± 17	-1.3
					SR 6	7 ± 9	26 ± 15	47 ± 16	28
					SR 7	8 ± 9	21 ± 12	42 ± 13	30

Examination of Figure 9 and Table 4 shows karst inflows are the significant driver for increases in instream flows. The large karst inflows are offset by significant losses from streamflow to groundwater resulting in relatively moderate net changes in flow.

Discussion

The analysis conducted shows a predominantly gaining river with significant karst inflows and groundwater losses occurring at a sub-reach scale. Mass balance analysis at the sub-reach scale is necessary for determining how changing flow regimes due to climate change may affect future flows. Under low flow conditions, rivers and karst springs in mountainous karst watersheds may be at risk of running dry. Delineating river sections with significant exchange allows water managers to better plan for low flow conditions.

Results of the reach scale analysis initially show the Logan River experiences a net increase in flow between Franklin Basin GAMUT and Dewitt Springs Campground (Figure 4). Comparison of the flow data using Eqn. 1, 2, and 3 shows: Rick's Spring and Dewitt Springs combined account for 40% ± 18% of the instream flow between Tony Grove GAMUT and Dewitt Springs Campground; between Tony Grove GAMUT and Wood Camp, Rick's Spring is 20% ± 12% of the observed flow; and between Wood Camp and Dewitt Springs Campground, Dewitt Springs accounts for 8% ± 4% of the observed upstream flow. The influence of the gauged karst conduits on instream flow is the greatest in the summer and winter months with little or no influence during the spring (Figure 5). This indicates the importance of the karst conduits in regulating baseflow.

Analysis at the sub-reach scale using combined flow and mass balance equations (Eqns. 4 and 6) show significant karst and matrix inflows and groundwater losses simultaneously occurring within sub-reaches (Table 4). This is consistent with gauging stations showing dominant net gains or net losses at the reach scale during the same time period (Figure 5). The mass balance analysis further reveals the karst inflows and groundwater losses are significantly larger than the matrix inflows (Figure 9, Table 4). Comparison of the average magnitude of the karst inflow and groundwater loss to the calculated net groundwater-surface water exchange for each sub-reach (Table 4) shows the net flow balance does not represent the gross magnitude of groundwater-surface water exchange simultaneously occurring within each sub-reach. The magnitude of the groundwater losses indicates diffuse karst features are draining water away from the river creating the large groundwater losses. The Logan River could potentially run dry in some areas were losses tend to exceed gains under the right flow regime. The magnitude of karst inflows vary with annual snowpack and precipitation events [*Spangler*, 2011]. The magnitude of groundwater losses due to kart features are likely more consistent with some variation due to depth or flow volume in the river.

Understanding the dynamics of the losses occurring within the watershed is critical for predicting where and under what flow regime portions of the river may be at risk of running dry. This is particularly relevant given growing concerns over the effects of climate change on annual snowpack in the western United States [*Tague et al.*, 2008] and the potential impact on karst groundwater recharge and discharge. At a national scale the effect of variable recharge to karst springs is of interest because karst watersheds account for 20% of the US land surface and provide 40% of US drinking water sourced from groundwater [*USGS*, 2017]. At a local scale, the potential for portions of the watershed to run dry is particularly relevant to the municipalities and agricultural interests within Cache Valley. Additionally, understanding the dynamics of the karst springs under baseflow conditions given variable snowpack conditions is of interest to Logan City because of Dewitt Springs' role as a drinking water source.

Recommendations for Future Work

At the reach scale, efforts should be made to make time variable estimates of the gross groundwater inflows and groundwater losses to detect temporal trends in groundwater-surface water exchanges. These estimates could be made using a mass balance approach with specific conductivity as the tracer. This would require collecting continuous specific conductivity data at main stem gauges, tributaries, and karst springs. Additionally, measuring flow at the remaining ungauged karst springs or major karst features, such as Wood Camp Spring, would be necessary to account for their contributions to the mass balance. This could be done by gauging springs directly or using differential gauging of the main stem. At a smaller spatial scale, tracer studies could be used to quantify the losses occurring between the sub-reach cross sections. This provides information about the Q_{loss} term in Eqns. 5 and 6, which would reduce the uncertainty in the sub-reach estimates of groundwater-surface water exchanges.

Conclusion

The Logan River watershed is heavily influenced by karst geology at varying spatial and temporal scales. Analysis at a reach scale showed significant flow contributions from karst springs. The temporal trend was shown to be consistent when the karst springs were accounted for or removed when calculating the net groundwater-surface water interaction in each reach indicating the presence of un-gauged diffuse karst features present in the watershed. Use of a mass balance to quantify the potential range of matrix and karst inflows and surface water losses at a sub-reach scale revealed the presence of significant simultaneous inflows and losses. It is suspected that these significant simultaneous gains and losses are due to karst features both discharging to the river and draining water away from the river.

The responsiveness of karst features to changes in annual snowpack makes them a highly variable source of groundwater flow. Shifting climate conditions have increased the dependence of western watersheds on longer groundwater flowpaths to provide streamflow during baseflow conditions. The lack of matrix flow observed in this project highlights the need to quantify both matrix and karst flows in karst watersheds for effective watershed management given shifting climate conditions.

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Appendix A

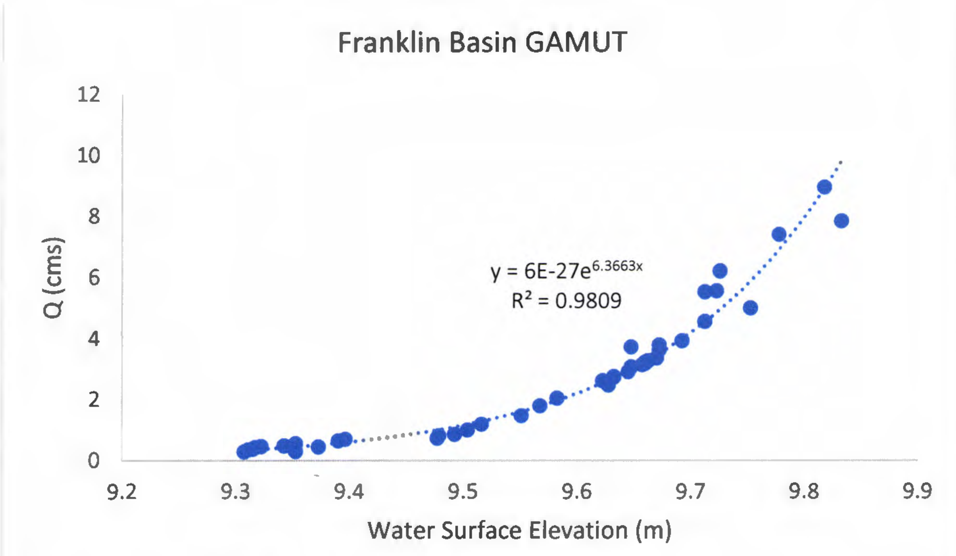

Figure A1. Franklin Basin GAMUT rating curve.

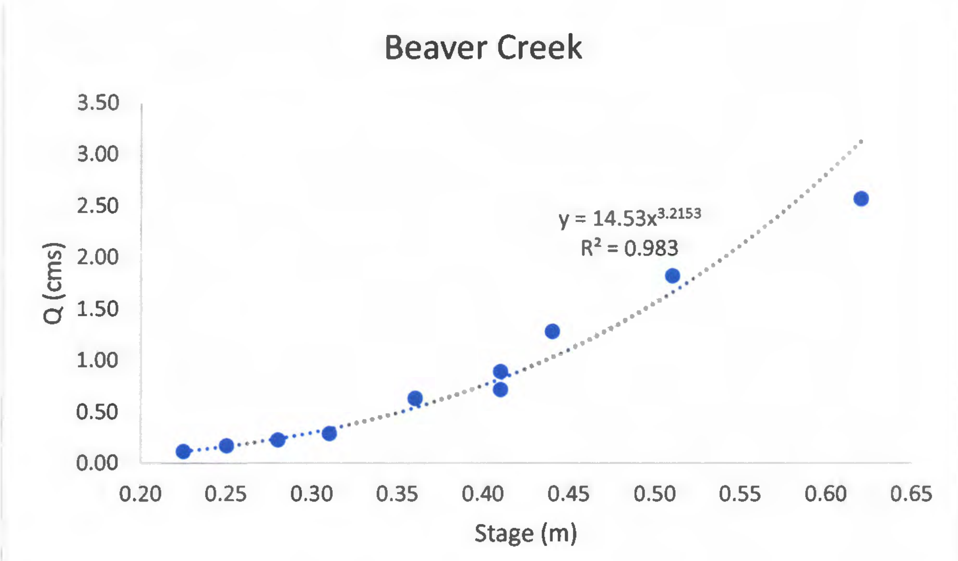

Figure A2. Beaver Creek rating curve.

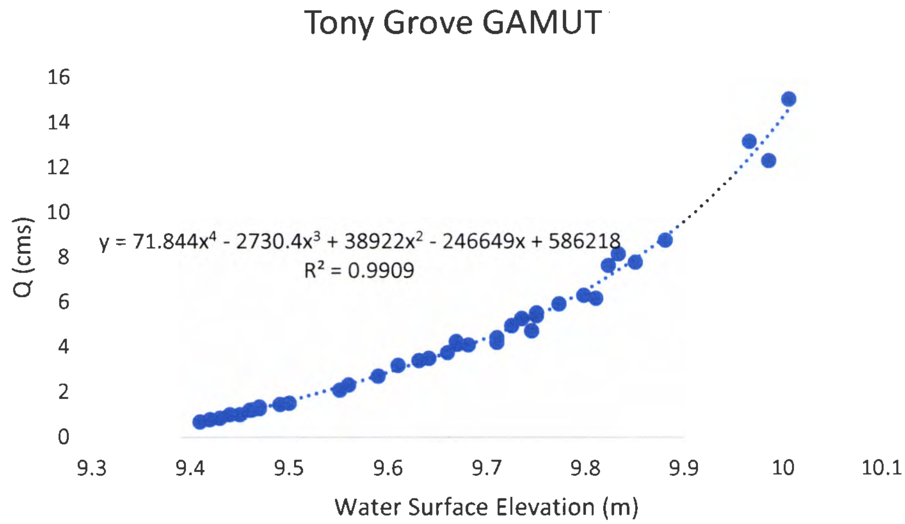

Figure A3. Tony Grove GAMUT rating curve.

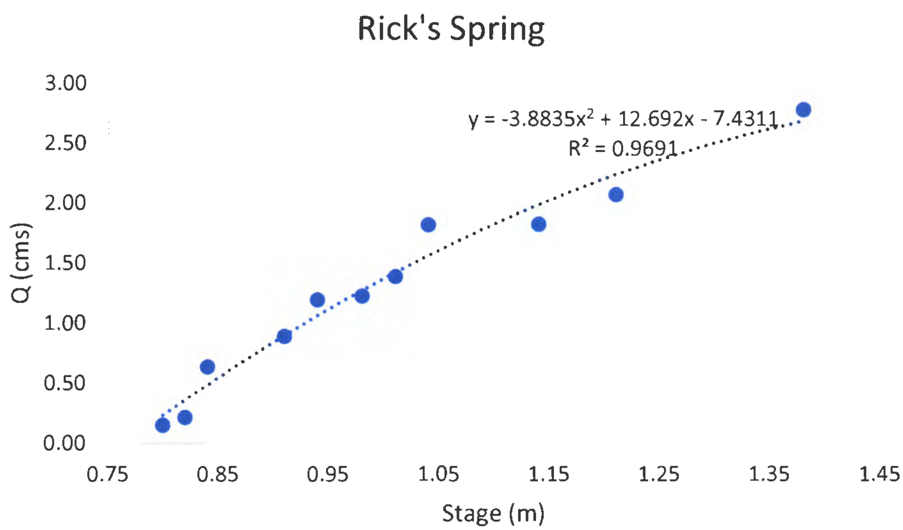

Figure A4. Rick's Spring rating curve.

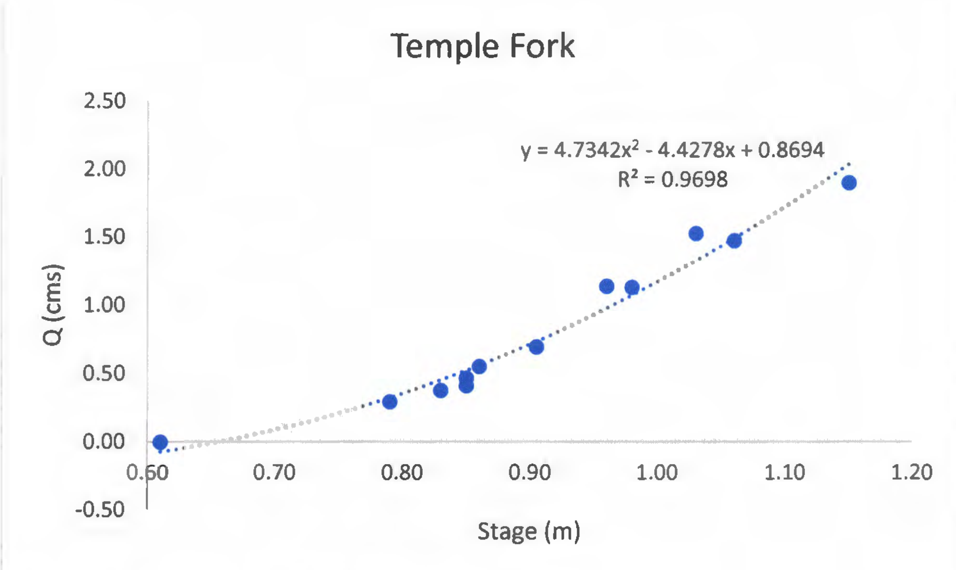

Figure A5. Temple Fork rating curve.

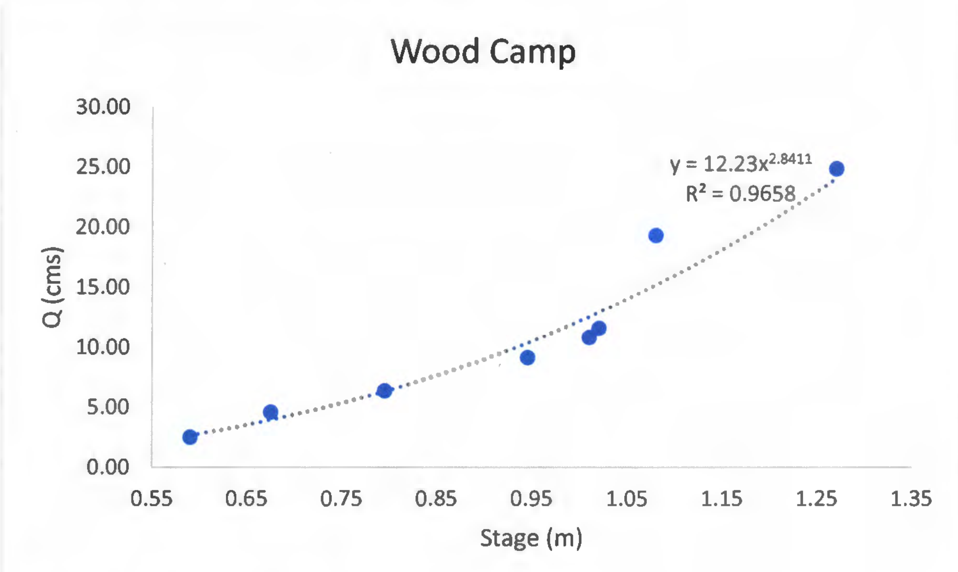

Figure A6. Wood Camp rating curve.

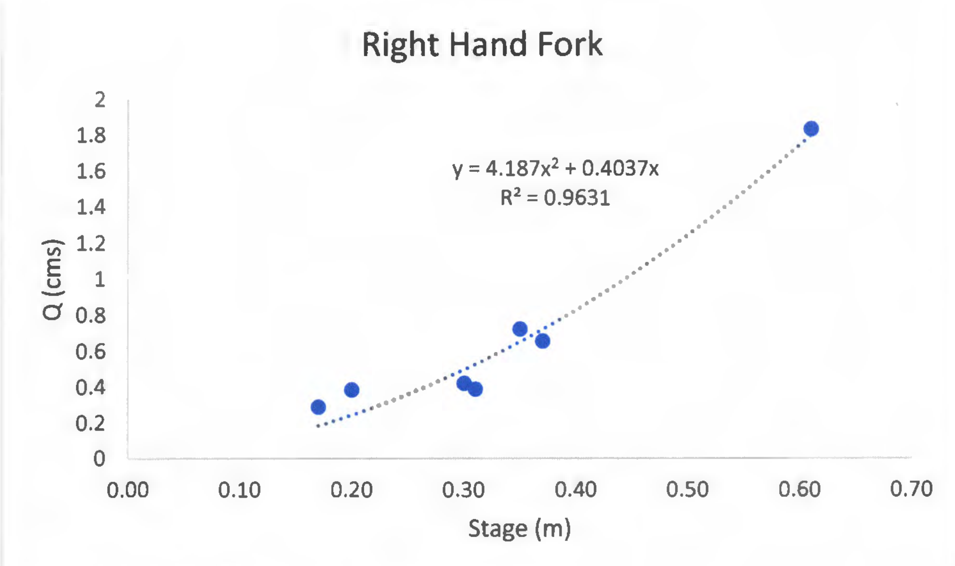

Figure A7. Right Hand Fork rating curve.

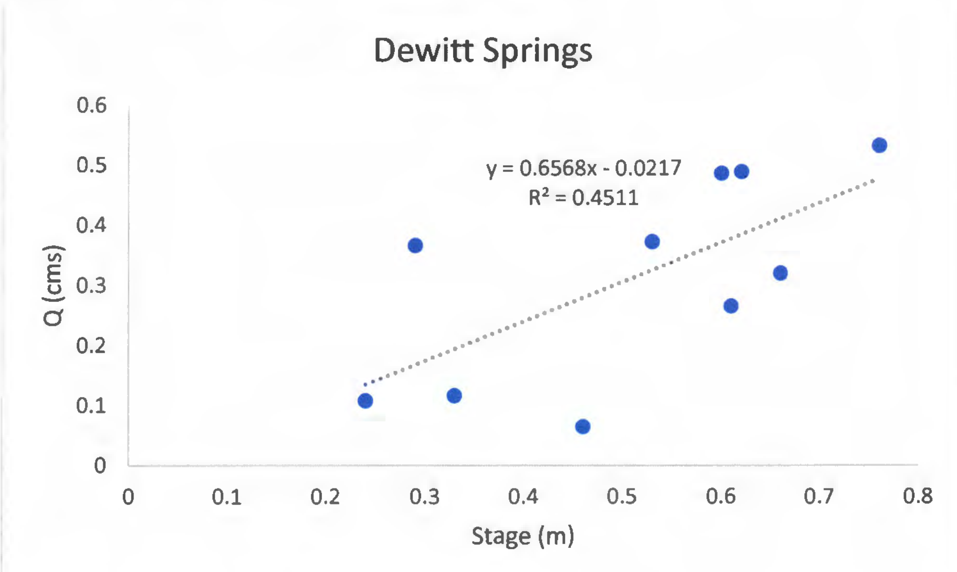

Figure A8. Dewitt Springs rating curve.

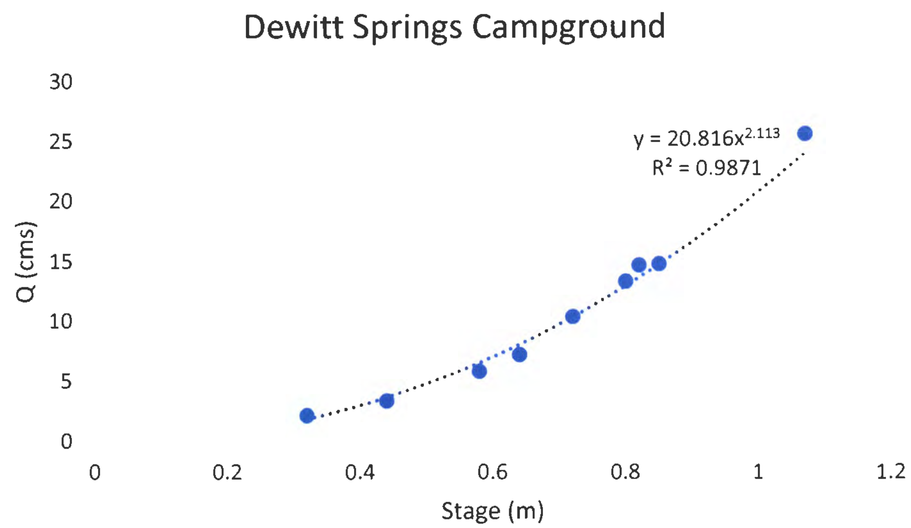

Figure A9. Dewitt Springs Campground rating curve.

Appendix B

Table B1. June 2014 discharge measurements.

Site Name	Site Code	Type	Date	Time	Discharge (cms)	Temperature (°C)	Conductivity (uS/cm)	SpCond (uS/cm)	Comments
Tony Grove GAMUT	TGG	MS	7/9/2014	10:00	2.75	9.55	229	325	
Theurer Creek	TC	Trib	7/9/2014	11:00	0.00	12.96	229	298	
Culvert Tributary	CT	Trib	7/9/2014	17:45	0.00	13.49	341	438	
Cattle Guard	CG	MS	7/9/2015	16:30	2.61	16.56	261	311	
Rick's Spring	RS	Spring	7/9/2014	13:00	0.51	6.81	227	349	
Above Temple Fork	ATF	MS	7/9/2014	15:00	3.14	14.39	252	317	
Temple Fork	TF	Trib	7/9/2014	14:00	0.55	14.05	271	342	
Pullout	PO	MS	7/10/2014	13:00	4.10	11.54	245	330	
Logan Cave Spring	BC	Spring	7/10/2014	14:15	0.05	7.56	242	363	
Wood Camp	WC	MS	7/10/2014	11:45	5.04	10.65	243	335	
Above Right Hand Fork	ARF	MS	7/10/2014	10:30	5.65	9.81	236	332	
Right Hand Fork	RHF	Trib	7/10/2014	9:30	0.20	11.2	304	412	
Chokecherry	CC	MS	7/10/2014	13:45	5.56	12.86	251	326	
Dewitt Springs	DS	Spring	7/10/2014	17:00	0.39	6.7	209	321	
Dewitt Springs Campground	DSC	MS	7/11/2014	9:45	5.40	12.79	252	346	

Table B2. August 2014 discharge measurements.

Description	Site Code	Type	Date	Time	Discharge (cms)	Temperature (°C)	Conductivity (uS/cm)	SpCond (uS/cm)	Comments
Tony Grove GAMUT	TGG	MS	8/18/2014	10:30	1.33	11.11	251	342	
Theurer Creek	TC	Trib	8/18/2014	11:45	0.00	10.67	353	486	
Culvert Tributary	CT	Trib	8/18/2014	12:15	0.00	10.67	353	486	
Cattle Guard	CG	MS	8/18/2014	13:15	1.46	15.11	268	331	
Rick's Spring	RS	Spring	8/18/2014	15:00	0.22	6.92	228	348	
Above Temple Fork	ATF	MS	8/18/2014	16:45	1.48	16.3	265	318	
Temple Fork	TF	Trib	8/18/2014	15:45	0.45	16.23	272	327	
Pullout	PO	MS	8/19/2014	9:30	2.25	10.42	253	351	
Logan Cave Spring	BC	Spring	8/18/2014	17:30	0.03	7.67	256	382	
Wood Camp	WC	MS	8/19/2014	10:15	3.09	10.64	253	348	
Above Right Hand Fork	ARF	MS	8/19/2014	11:30	3.08	10.29	247	344	
Right Hand Fork	RHF	Trib	8/19/2014	12:30	0.23	11.26	295	400	
ChokeCherry	CC	MS	8/19/2014	13:45	3.24	10.94	253	346	
Dewitt Springs	DS	Spring	8/19/2014	15:00	0.10	7.16	229	347	
Dewitt Springs Campground	DSC	MS	8/19/2014	16:15	3.43	11.98	263	350	

Table B3. December 2014 discharge measurements.

Site Name	Site Code	Type	Date	Time	Discharge (cms)	Temperature (°C)	Conductivity (uS/cm)	SpCond (uS/cm)	Comments
Tony's Grove GAMUT	TGG	MS	12/15/2014	10:15	0.60	0.34	193	364	
Cattle Guard	CG	MS	12/15/2014	12:30	0.72	1.2	197	362	
Rick's Spring	RS	Spring	12/15/2014	4:15	0.03	7.07	219	333	
Above Temple Fork	ATF	MS	12/16/2014	10:30	0.65	1.67	211	380	
Temple Fork	TF	Trib	12/16/2014	9:15	0.33	1.1	190	350	
Pullout	PO	MS	12/16/2014	12:00	1.10	1.8	203	364	
Logan Cave Spring	BCS	Spring	12/15/2014	16:00	0.03	7.42	262	395	
Wood Camp	WC	MS	12/16/2014	13:15	1.67	2.42	203	357	
Above Right Hand Fork	ARF	MS	12/16/2014	14:30	1.77	3.45	209	355	
Right Hand Fork	RHF	Trib	12/16/2014	15:15	0.20	6.62	258	398	
ChokeCherry	CC	MS	12/16/2014	16:14	2.20	3.99	215	359	
Dewitt Springs	DS	Spring	12/17/2014	8:30	0.10	7.41	250	376	
Dewitt Springs Campground	DSC	MS	12/17/2014	9:30	2.04	3.52	216	367	

Table B4. June 2015 measurements.

Site Name	Site Code	Type	Date	Time	Discharge (cms)	Temperature (°C)	Conductivity (uS/cm)	SpCond (uS/cm)	Comments
Franklin Basin GAMUT	FBG	MS	6/25/2015	16:00	1.83	9.01	200	288	
Franklin Culvert (Bridge)	FC	MS	6/25/2015	11:00	1.84	8.85	201	291	
Beaver Creek	BC	Trib	6/25/2015	14:00	0.29	12.64	308	406	
White Pine Creek	WPC	Trib	6/25/2015	13:00	0.04	15.57	291	355	
Red Banks Campground	RBC	MS	6/25/2015	12:15	3.08	11.83	235	314	
Tony Grove Creek	TGC	Trib	6/25/2015	11:15	0.01			439	Dilution gauging
Tony's Grove GAMUT	TGG	MS	6/24/2015	18:00	3.32	14.28	250	314	
Cattle Guard	CG	MS	6/24/2015	18:15	3.12	15.39	252	308	
Rick's Spring	RS	Spring	6/24/2015	17:15	0.64	6.47	224	347	
Above Temple Fork	ATF	MS	6/24/2015	15:30	4.08	14.17	243	306	
Temple Fork	TF	Trib	6/24/2015	17:15	0.47	16.54	279	332	
Pullout	PO	MS	6/24/2015	14:00	4.91	13.2	244	315	
Logan Cave Spring	BCS	Spring	6/24/2015	16:00	0.05	7.41	237	357	
Wood Camp Spring	WCS	Spring	6/24/2015	16:00	NA				
Wood Camp	WC	MS	6/24/2015	13:54	6.20				
Above Right Hand Fork	ARF	MS	6/24/2015	12:15	6.38	10.24	228	318	
Right Hand Fork	RHF	Trib	6/24/2015	13:00	0.25	12.82	311	406	
ChokeCherry	CC	MS	6/24/2015	11:45	6.36	9.59	231	327	
Dewitt Springs	DS	Spring	6/24/2015	11:00	0.18	6.71	216	331	
Dewitt Springs Campground	DSC	MS	6/23/2015	15:00	7.26	11.6	240	322	

Table B5. August 2015 measurements.

Site Name	Site Code	Type	Date	Time	Discharge (cms)	Temperature (°C)	Conductivity (uS/cm)	SpCond (uS/cm)	% Sat	DO (mg/L)	pH	Comments
Franklin Basin GAMUT	FBG	MS	8/19/2015	14:45	0.5240	10.64	230.6	317.8	82.2	9.13	8.68	
Franklin Culvert (Bridge)	FC	MS	8/19/2015	13:00	0.4493	9.55	226.0	320.7	80.9	9.22	8.68	
Beaver Creek	BC	Trib	8/19/2015	11:15	0.1171	10.36	300.5	417.1	77.6	8.67	8.41	
White Pine Creek	WPC	Trib	8/19/2015	13:15	0.0036	15.01	305.0	378.0	90.3	9.1	8.54	Dilution gauging
Red Banks Campground	RBC	MS	8/19/2015	10:00	1.1773	8.37	240.0	351.8	82.4	9.67	8.65	
Tony Grove Creek	TGC	Trib	8/19/2015	12:15	0.0037	11.85	337.0	450.0	76.9	8.3	8.25	Dilution gauging
Little Bear Creek	LBC	Trib	8/19/2015	11:00	0.1250	10.30	274.0	381.0	79.7	8.92	8.21	Dilution gauging
Tony Grove GAMUT	TGG	MS	8/19/2015	9:45	1.1600	8.36	242.0	355.0	82.0	9.62	8.45	
Cattle Guard	CG	MS	8/19/2015	10:00	1.1293	9.03	247.0	355.0	84.1	9.7	8.71	
Rick's Spring	RS	Trib	8/19/2015	14:45	0.1562	6.98	235.0	358.0	78.8	9.55	7.65	
Above Temple Fork	ATF	MS	8/19/2015	11:15	1.4688	10.43	253.0	351.0	84.6	9.44	8.74	
Temple Fork	TF	Trib	8/19/2015	14:00	0.3787	13.12	254.0	329.0	82.8	8.7	9.03	
Pullout	PO	MS	8/19/2015	13:00	1.8280	11.86	256.0	341.0	88.1	9.52	9.15	
Pullout	PO	MS	8/18/2015	16:15	1.9209	14.23	261.0	329.0	87.1	8.93	8.91	
Pullout Spring	POS	Trib	8/18/2015	16:30	NA	6.88	306.0	468.0	76.7	9.33	7.63	
Logan Cave Spring	BCS	Trib	8/18/2015	11:30	0.0296	7.70	263.0	392.0	82.3	9.79	7.99	
Above Wood Camp	AWC	MS	8/18/2015	14:45	2.3057	13.20	260.0	334.0	86.5	9.05	8.92	
Wood Camp Spring	WCS	Trib	8/18/2015	14:15	NA	6.25	209.0	326.0	79.8	9.87	7.72	
Wood Camp	WC	MS	8/18/2015	13:30	2.4633	11.84	255.0	340.0	86.3	9.33	8.66	
Above Right Hand Fork	ARF	MS	8/18/2015	11:30	2.4580	9.55	246.0	349.0	83.9	9.56	8.45	
Right Hand Fork	RHF	Trib	8/18/2015	10:15	0.1826	9.56	288.0	409.0	82.9	9.5	8.08	
ChokeCherry	CC	MS	8/18/2015	9:30	2.5854	8.75	247.0	358.0	83.9	9.75	8.4	
Dewitt Springs	DS	Trib	8/18/2015	13:30	0.3677	6.85	219.0	336.0	81.1	9.85	7.57	
Dewitt Springs Campground	DSC	MS	8/18/2015	14:15	3.3716	11.51	262.0	352.0	87.6	9.55	8.35	

Table B6. May 2016 measurements.

Site Name	Site Code	Type	Date	Time	Discharge (cms)	Temperature (°C)	Conductivity (uS/cm)	SpCond (uS/cm)	pH	Comments
Franklin Culvert	FC	MS	5/17/2016	10:50	5.5	4.71	123	200	8.31	Flow was measured using truck
Beaver Creek	BC	Trib	5/17/2016	11:45	0.9	6.16	219	342	8.51	
White Pine Creek	WPC	Trib	5/17/2016	12:45	0.3	5.8	204	322	8.76	
Tony Grove Creek	TGC	Trib	5/17/2016	13:45	0.1	7.19	185	281	8.38	
Little Bear Creek	LBC	Trib	5/17/2016	14:30	0.1	8.41	221	324	8.71	
Tony Grove GAMUT	TGG	MS	5/17/2016	15:30	6.8	7.75	166	248	8.74	
Ricks Spring	RS	Spring	5/18/2016	10:00	1.4	5.85	210	331	7.66	
Temple Fork	TF	Trib	5/18/2016	11:15	1.1	7.27	224	338	8.73	
Temple Fork Spring	TFS	Spring	5/18/2016	11:00	NA	9.29	274	392	7.82	
Cottonwood Main Stem	CMS	MS	5/18/2016	13:15	9.9	7.57	183	274	8.75	
Cottonwood Canyon	CWC	Trib	5/18/2016	13:45	0.3	8.08	219	324	8.8	
Logan Cave Spring	BCS	Spring	5/18/2016	15:00	0.1	6.46	208	323	8.17	
Above Wood Camp	AWC	MS	5/18/2016	15:30	10.9	8.95	192	277	8.78	
Wood Camp	WC	MS	5/19/2016	11:00	12.2					
Juniper	J	Trib	5/19/2016	9:45	0.5	8.66	223	338	8.66	
Lower Wood Camp Spring	LWC	Spring	5/19/2016	11:00	0.0	8.03	346	512	7.92	
Right Hand Fork	RHF	Trib	5/19/2016	11:45	0.4	10.46	288	389	8.76	
Card Canyon	CCC	Trib	5/19/2016	12:30	0.0	12.14	155	206	8.75	
Below Card Canyon	ACC	MS	5/19/2016	13:30	14.1	8.12	198	293	8.68	
Dewitt Springs	DS	Spring	5/19/2016	14:15	0.5	6.36	202	313	8.02	
Dewitt Springs Campground	DSC	MS	5/19/2016	14:30	14.8	8.77	209	303	8.55	

Table B7. Sodium and Calcium ion concentrations.

		Sodium (mg/L)					Calcium (mg/L)				
Site Name	**Classification**	**Jun-15**	**Aug-15**	**Feb-16**	**May-16**	**Jul-17**	**Jun-15**	**Aug-15**	**Feb-16**	**May-16**	**Jul-17**
Franklin Basin GAMUT	Logan River	1.18	1.35		0.82	1.02	48.38	49.39		11.95	20.98
Franklin Culvert (Bridge)	Logan River	0.59	1.37				24.32	49.58			
Red Banks Campground	Logan River	1.85	2.30			1.65	48.24	51.89			16.05
Tony's Grove GAMUT	Logan River	2.19	2.42		2.05	1.72	46.34	51.45		10.10	16.61
Cattle Guard	Logan River	2.05	2.48				47.43	51.42			
LR at Ricks Spring	Logan River					1.43					23.11
Above Temple Fork	Logan River	2.09	2.62				46.55	50.69			
Pullout	Logan River	2.28	2.69				48.64	46.52			
Cottonwood Main Stem	Logan River				1.75					7.26	
Wood Camp	Logan River	2.20	2.77		2.55	2.12	45.71	48.51		42.25	18.38
Above Right Hand Fork	Logan River	2.23	2.55				47.77	48.88			
ChokeCherry	Logan River	2.30	2.88				46.08	49.70			
Below Card Canyon	Logan River				2.28					11.58	
Guanavah Campground	Logan River					2.31					21.81
Beaver Spring	Spring					1.22					26.59
Mud Spring	Spring					3.01					35.53
Coldwater spring	Spring					1.31					39.05
Rick's Springs	Spring	1.83	2.32	9.10	1.18	1.59	52.91	52.14	56.53	17.46	29.82
Hidden Spring	Spring					7.47					31.01
Temple Fork Spring	Spring			4.56	3.95				52.97	17.36	
Pullout Spring	Spring		5.12	4.42				61.06	49.52		
Cottonwood Creek	Tributary									17.72	
Logan Cave Spring	Spring	1.58	1.75	1.88	1.05	1.88	53.35	55.46	56.50	47.79	21.65
Wood Camp Spring	Spring	1.59	0.99	0.34	0.82	0.69	55.59	39.70	13.27	41.15	14.12
China Row Spring	Spring					15.17					26.53
Unnamed Spring	Spring					6.32					44.79

Malibu Campground Spring	Spring					0.87					25.61
Wind Caves Spring	Spring					2.91					33.34
Dewitt Springs	Spring	2.07	1.57	2.90	1.05		49.75	49.34	47.23	15.06	
Dewitt Springs Campground	Logan River	2.53	2.96		2.79		48.16	50.68		39.69	
Beaver Creek	Tributary		4.67		6.62			55.18		14.71	
White Pine Creek	Tributary	1.21	2.65		0.83		49.38	51.16		41.03	
Tony Grove Creek	Tributary	2.49	2.86		1.75		68.41	67.78		15.24	
Little Bear Creek	Tributary		2.60		1.77			49.07		39.98	
Temple Fork	Tributary	2.60	2.59		1.77		52.86	48.44			
Jardine	Tributary									18.35	
Right Hand Fork	Tributary	5.01	4.59				60.45	55.58			
Card Canyon	Tributary				3.78					6.40	
Spring Hollow Creek	Tributary	52.40	2.05				52.40	53.47		20.83	
Red Banks Well	Well					12.90					34.12

Table B8. Magnesium and Chloride ion concentrations.

		Magnesium (mg/L)					Chloride (mg/L)				
Site Name	**Classification**	**Jun-15**	**Aug-15**	**Feb-16**	**May-16**	**Jul-17**	**Jun-15**	**Aug-15**	**Feb-16**	**May-16**	**Jul-17**
Franklin Basin GAMUT	Logan River	10.39	14.50		1.69	8.78	0.98	1.13		0.83	0.92
Franklin Culvert (Bridge)	Logan River	5.35	14.36				0.98	1.10			
Red Banks Campground	Logan River	14.02	15.59			12.89	2.24	2.65			1.84
Tony's Grove GAMUT	Logan River	13.46	16.45		1.56	12.86	2.45	2.91		3.37	1.94
Cattle Guard	Logan River	13.50	16.82				2.53	2.96			
LR at Ricks Spring	Logan River					16.56					2.11
Above Temple Fork	Logan River	13.57	16.76				2.61	2.96		2.37	
Pullout	Logan River	13.79	13.71				2.76	3.06			
Cottonwood Main Stem	Logan River				1.34					3.34	
Wood Camp	Logan River	13.87	14.16		9.94	14.25	2.77	3.20		3.01	2.25

Above Right Hand Fork	Logan River	14.78	15.38				1.62	2.95			
ChokeCherry	Logan River	14.58	17.50				2.98	3.31			
Below Card Canyon	Logan River				2.38					3.63	
Guanavah Campground	Logan River					14.91					2.53
Beaver Spring	Spring					8.90					0.99
Mud Spring	Spring					26.05					2.79
Coldwater spring	Spring					3.76					1.12
Rick's Springs	Spring	14.79	14.40	15.41	3.83	14.31	1.86	1.95	16.10	1.64	1.48
Hidden Spring	Spring					2.79					6.63
Temple Fork Spring	Spring			17.50	4.75				6.34	7.44	
Pullout Spring	Spring		19.49	19.02				6.88	6.16		
Cottonwood Creek	Tributary				4.11					1.10	
Logan Cave Spring	Spring	19.06	19.71	19.82	5.48	13.92	5.39	1.62	2.31	1.18	1.45
Wood Camp Spring	Spring	18.13	15.61	6.44	17.80	15.01	1.06	1.04	0.99	0.96	0.78
China Row Spring	Spring					19.57					17.91
Unnamed Spring	Spring					22.99					8.00
Malibu Campground Spring	Spring					11.12					1.14
Wind Caves Spring	Spring					17.98					2.53
Dewitt Springs	Spring	13.55	15.43	18.36	2.26		2.21	1.46	3.94	1.51	
Dewitt Springs Campground	Logan River	14.60	17.74		4.17		3.16	3.29		3.99	
Beaver Creek	Tributary		22.23		3.18		5.39	7.06		11.55	
White Pine Creek	Tributary	20.37	22.46		17.17		0.98	2.52		0.94	
Tony Grove Creek	Tributary	20.62	20.09		3.48		1.72	2.37		1.65	
Little Bear Creek	Tributary		21.69		13.22			2.51		1.48	
Temple Fork	Tributary	14.73	14.57				2.51	2.48		4.65	
Jardine	Tributary				4.23					1.25	
Right Hand Fork	Tributary	18.07	17.35				5.33	5.35			
Card Canyon	Tributary				1.84					5.34	
Spring Hollow Creek	Tributary	13.12	14.77		2.70		1.50	1.54		1.39	
Red Banks Well	Well					17.35					39.43

Table B9. Sulfate ion concentrations and site coordinates.

		Sulfate (mg/L)						
Site Name	Classification	Jun-15	Aug-15	Feb-16	May-16	Jul-17	Latitude	Longitude
Franklin Basin GAMUT	Logan River	1.26	1.61		1.06	1.00	41.9502	-111.580553
Franklin Culvert (Bridge)	Logan River	1.18	1.51				41.933149	-111.566331
Red Banks Campground	Logan River	1.33	1.57			1.10	41.897969	-111.565303
Tony's Grove GAMUT	Logan River	1.40	1.61		1.27	1.17	41.87606667	-111.5646667
Cattle Guard	Logan River	1.31	1.57				41.85591667	-111.5786667
LR at Ricks Spring	Logan River					1.27	41.840229	-111.587254
Above Temple Fork	Logan River	1.40	1.68				41.83406667	-111.5924167
Pullout	Logan River	1.51	2.14				41.81865	-111.6159667
Cottonwood Main Stem	Logan River				1.40		41.81329	-111.621206
Wood Camp	Logan River	1.60	2.06		1.31	1.53	41.79676667	-111.64535
Above Right Hand Fork	Logan River	0.97	1.93				41.78423333	-111.6411833
ChokeCherry	Logan River	1.66	2.23				41.77015	-111.6581167
Below Card Canyon	Logan River				1.66		41.766005	-111.666747
Guanavah Campground	Logan River					1.96	41.76215	-111.698066
Beaver Spring	Spring					1.10	41.950947	-111.584328
Mud Spring	Spring					2.62	41.885445	-111.572324
Coldwater spring	Spring					1.02	41.882263	-111.646079
Rick's Springs	Spring	1.38	1.69	1.62	1.21	1.34	41.84008333	-111.5887167
Hidden Spring	Spring					4.69	41.829398	-111.586875
Temple Fork Spring	Spring			2.12	2.82		41.833188	-111.593129
Pullout Spring	Spring		6.34	4.25			41.8185	-111.615684
Cottonwood Creek	Tributary				1.88		41.814079	-111.620489

Logan Cave Spring	Spring	2.59	3.78	4.45	1.83	2.74	41.81388333	- 111.6243333
Wood Camp Spring	Spring	2.24	1.80	1.80	1.24	0.89	41.798479	-111.644072
China Row Spring	Spring					3.97	41.793829	-11.645771
Unnamed Spring	Spring					5.23	41.780717	-111.659067
Malibu Campground Spring	Spring					8.75	41.766783	-111.6951
Wind Caves Spring	Spring					15.83	41.760549	-111.709546
Dewitt Springs	Spring	5.36	6.56	7.49	2.99		41.75943333	-111.70775
Dewitt Springs Campground	Logan River	2.44	3.16		2.17		41.75711667	-111.7089
Beaver Creek	Tributary		1.87		1.62		41.93055	-111.5619
White Pine Creek	Tributary	1.01	1.72		1.15		41.906633	-111.564033
Tony Grove Creek	Tributary	1.00	0.93		1.23		41.886339	-111.564161
Little Bear Creek	Tributary		3.34		2.42		41.878087	-111.563218
Temple Fork	Tributary	2.84	3.03				41.83421667	-111.5916
Jardine	Tributary				1.92		41.796616	-111.646451
Right Hand Fork	Tributary	4.86	4.92				41.78116667	- 111.6390667
Card Canyon	Tributary				2.55		41.766595	-111.664306
Spring Hollow Creek	Tributary	7.20	10.37		4.48		41.75046667	-111.7171
Red Banks Well	Well					2.21	41.898403	-111.56461

Appendix C

Table C1. Results from June 2015 mass balance using Sodium.

	Sodium								
AVG	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.10	26.50	0.51	1.85	1.62	0.92	5.33	27.80	72.42
SR 1 OI	0.07	26.50	0.51	1.18	1.64	0.92	4.06	27.80	73.70
SR 2 IO	0.17	26.50	0.51	2.09	1.35	0.92	5.37	16.57	43.85
SR 2 OI	0.16	26.50	0.51	1.85	1.36	0.92	5.09	16.57	44.12
SR 3 IO	0.20	26.50	0.51	2.23	2.56	0.92	4.83	12.49	52.47
SR 3 OI	0.19	26.50	0.51	2.09	2.57	0.92	4.71	12.49	52.59
SR 4 IO	0.15	26.90	0.51	2.53	0.98	1.58	2.42	8.02	15.40
SR 4 OI	0.15	26.84	0.51	2.23	0.99	1.58	2.28	8.03	15.54
STDDEV	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.13	13.60	0.29	0.00	0.30	0.58	7.18	15.73	16.41
SR 1 OI	0.11	13.60	0.29	0.00	0.31	0.58	6.23	15.73	16.71
SR 2 IO	0.19	13.60	0.29	0.00	0.33	0.58	6.15	9.38	10.60
SR 2 OI	0.18	13.60	0.29	0.00	0.33	0.58	5.84	9.38	10.56
SR 3 IO	0.24	13.60	0.29	0.00	0.36	0.58	5.95	7.07	8.76
SR 3 OI	0.24	13.60	0.29	0.00	0.36	0.58	5.83	7.07	8.73
SR 4 IO	0.18	13.36	0.29	0.00	0.32	1.05	2.85	4.52	5.04
SR 4 OI	0.18	13.40	0.29	0.00	0.32	1.05	2.78	4.52	5.08
MAX	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	1.22	50.00	1.00	1.85	2.19	1.50	66.48	54.51	119.37
SR 1 OI	0.97	50.00	1.00	1.18	2.20	1.50	52.84	54.51	120.12
SR 2 IO	1.59	50.00	1.00	2.09	1.97	1.50	51.56	32.49	63.86
SR 2 OI	1.50	50.00	1.00	1.85	1.97	1.50	48.58	32.49	64.03
SR 3 IO	2.08	50.00	1.00	2.23	3.21	1.50	51.04	24.49	78.66
SR 3 OI	2.03	50.00	1.00	2.09	3.21	1.50	49.72	24.49	78.73
SR 4 IO	1.59	50.00	1.00	2.53	1.61	2.90	24.91	15.67	25.23
SR 4 OI	1.60	50.00	1.00	2.23	1.62	2.90	25.00	15.67	25.33
MIN	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.01	3.00	0.02	1.85	0.56	0.34	0.39	1.09	30.47
SR 1 OI	0.00	3.00	0.02	1.18	0.56	0.34	0.02	1.09	30.74
SR 2 IO	0.03	3.00	0.02	2.09	0.08	0.34	0.88	0.65	2.67
SR 2 OI	0.03	3.00	0.02	1.85	0.08	0.34	0.88	0.65	2.73
SR 3 IO	0.02	3.00	0.02	2.23	0.88	0.34	0.53	0.49	21.58
SR 3 OI	0.02	3.00	0.02	2.09	0.88	0.34	0.53	0.49	21.61

SR 4 IO	0.01	3.40	0.02	2.53	0.00	0.34	0.23	0.31	0.00
SR 4 OI	0.01	3.20	0.02	2.23	0.00	0.34	0.13	0.31	0.03

Table C2. Results from June 2015 mass balance using Chloride.

	Chloride								
AVG	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.16	22.50	0.51	2.24	1.55	1.30	8.68	27.80	69.07
SR 1 OI	0.12	22.50	0.51	0.98	1.60	1.30	6.31	27.80	71.44
SR 2 IO	0.21	22.50	0.51	2.61	1.31	1.30	6.71	16.57	42.50
SR 2 OI	0.19	22.50	0.51	2.24	1.32	1.30	6.29	16.57	42.92
SR 3 IO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 3 OI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 4 IO	0.49	25.89	0.53	3.16	0.66	2.66	7.75	8.37	10.42
SR 4 OI	0.47	25.56	0.54	1.62	0.70	2.66	7.29	8.40	10.91
STDDEV	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.13	10.13	0.29	0.00	0.30	0.52	7.31	15.73	16.44
SR 1 OI	0.11	10.13	0.29	0.00	0.31	0.52	5.85	15.73	17.13
SR 2 IO	0.16	10.13	0.29	0.00	0.31	0.52	5.32	9.38	10.05
SR 2 OI	0.15	10.13	0.29	0.00	0.31	0.52	4.99	9.38	10.10
SR 3 IO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 3 OI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 4 IO	0.24	8.29	0.28	0.00	0.33	1.97	3.81	4.47	5.24
SR 4 OI	0.24	8.50	0.28	0.00	0.35	1.97	3.78	4.46	5.45
MAX	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.95	40.00	1.00	2.24	2.16	1.82	51.80	54.51	117.69
SR 1 OI	0.65	40.00	1.00	0.98	2.19	1.82	35.53	54.51	119.49
SR 2 IO	1.13	40.00	1.00	2.61	1.93	1.82	36.82	32.49	62.84
SR 2 OI	1.05	40.00	1.00	2.24	1.94	1.82	33.97	32.49	63.15
SR 3 IO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 3 OI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 4 IO	1.62	40.00	1.00	3.16	1.46	5.39	25.37	15.67	22.91
SR 4 OI	1.61	40.00	1.00	1.62	1.51	5.39	25.19	15.67	23.60
MIN	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.03	5.00	0.02	2.24	0.61	0.78	1.87	1.09	33.40
SR 1 OI	0.01	5.00	0.02	0.98	0.62	0.78	0.65	1.09	33.73
SR 2 IO	0.05	5.00	0.02	2.61	0.32	0.78	1.64	0.65	10.28
SR 2 OI	0.05	5.00	0.02	2.24	0.32	0.78	1.63	0.65	10.34
SR 3 IO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

SR 3 OI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 4 IO	0.16	8.90	0.02	3.16	0.00	0.78	2.56	0.31	0.01
SR 4 OI	0.12	8.00	0.02	1.62	0.00	0.78	1.86	0.31	0.00

Table C3. Results from June 2015 mass balance using Magnesium.

	Magnesium								
AVG	Qmatrix	Cmatrix	Qloss	Closs	Qkarst	Ckarst	%Qmatrix	%Qloss	%Qkarst
SR 1 IO	0.15	109.50	0.51	14.02	1.56	8.01	8.18	27.80	69.56
SR 1 OI	0.21	109.50	0.44	10.39	1.43	4.34	11.56	23.97	62.33
SR 2 IO	0.21	109.50	0.51	13.57	1.30	2.26	6.88	16.57	42.33
SR 2 OI	0.21	109.50	0.51	14.02	1.30	2.26	6.98	16.57	42.23
SR 3 IO	0.23	109.50	0.51	14.78	2.53	8.01	5.58	12.49	51.72
SR 3 OI	0.29	109.50	0.43	13.57	2.38	5.99	7.20	10.43	48.03
SR 4 IO	0.16	109.50	0.51	14.60	0.97	2.26	2.57	7.99	15.22
SR 4 OI	0.17	109.50	0.51	14.78	0.97	2.26	2.59	7.99	15.20
STDDEV	Qmatrix	Cmatrix	Qloss	Closs	Qkarst	Ckarst	%Qmatrix	%Qloss	%Qkarst
SR 1 IO	0.21	52.40	0.29	0.00	0.34	5.76	11.54	15.73	18.43
SR 1 OI	0.21	52.40	0.30	0.00	0.30	4.43	11.56	16.49	16.58
SR 2 IO	0.18	52.40	0.29	0.00	0.30	0.00	5.78	9.38	9.70
SR 2 OI	0.18	52.40	0.29	0.00	0.30	0.00	5.88	9.38	9.71
SR 3 IO	0.33	52.40	0.29	0.00	0.42	5.76	8.15	7.07	10.34
SR 3 OI	0.35	52.40	0.28	0.00	0.37	5.39	8.63	6.81	8.99
SR 4 IO	0.14	52.40	0.29	0.00	0.28	0.00	2.27	4.52	4.32
SR 4 OI	0.15	52.40	0.29	0.00	0.28	0.00	2.29	4.52	4.32
MAX	Qmatrix	Cmatrix	Qloss	Closs	Qkarst	Ckarst	%Qmatrix	%Qloss	%Qkarst
SR 1 IO	1.58	200.00	1.00	14.02	2.20	13.77	85.91	54.51	119.85
SR 1 OI	1.36	200.00	1.00	10.39	2.09	13.77	74.11	54.51	113.87
SR 2 IO	1.25	200.00	1.00	13.57	1.90	2.26	40.77	32.49	61.68
SR 2 OI	1.28	200.00	1.00	14.02	1.90	2.26	41.64	32.49	61.61
SR 3 IO	2.30	200.00	1.00	14.78	3.24	13.77	56.32	24.49	79.41
SR 3 OI	2.23	200.00	1.00	13.57	3.06	13.77	54.55	24.49	74.93
SR 4 IO	1.08	200.00	1.00	14.60	1.53	2.26	16.88	15.67	24.04
SR 4 OI	1.09	200.00	1.00	14.78	1.53	2.26	17.04	15.67	24.02
MIN	Qmatrix	Cmatrix	Qloss	Closs	Qkarst	Ckarst	%Qmatrix	%Qloss	%Qkarst
SR 1 IO	0.00	19.00	0.02	14.02	0.34	2.26	0.23	1.09	18.33
SR 1 OI	0.00	19.00	0.02	10.39	0.34	2.26	0.01	1.09	18.56
SR 2 IO	0.05	19.00	0.02	13.57	0.43	2.26	1.63	0.65	14.03
SR 2 OI	0.05	19.00	0.02	14.02	0.43	2.26	1.63	0.65	14.01

SR 3 IO	0.00	19.00	0.02	14.78	0.70	2.26	0.02	0.49	17.18
SR 3 OI	0.00	19.00	0.02	13.57	0.70	2.26	0.00	0.49	17.22
SR 4 IO	0.03	19.00	0.02	14.60	0.29	2.26	0.47	0.31	4.56
SR 4 OI	0.03	19.00	0.02	14.78	0.29	2.26	0.47	0.31	4.55

Table C4. Results from June 2015 mass balance using Calcium.

	Calcium								
AVG	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.32	128.00	0.60	48.24	1.48	21.16	17.45	32.46	64.95
SR 1 OI	0.32	128.00	0.60	48.38	1.48	21.16	17.51	32.46	64.89
SR 2 IO	0.27	128.00	0.51	46.55	1.25	26.18	8.66	16.57	40.55
SR 2 OI	0.28	128.00	0.51	48.24	1.24	26.18	9.03	16.57	40.18
SR 3 IO	0.43	128.00	0.52	47.77	2.34	25.78	10.49	12.85	47.16
SR 3 OI	0.42	128.00	0.52	46.55	2.35	25.78	10.29	12.85	47.36
SR 4 IO	0.28	128.00	0.51	48.16	0.86	26.18	4.33	7.99	13.46
SR 4 OI	0.27	128.00	0.51	47.77	0.86	26.18	4.29	7.99	13.50
STDDEV	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.27	41.71	0.28	0.00	0.40	11.89	14.78	15.36	21.77
SR 1 OI	0.27	41.71	0.28	0.00	0.40	11.89	14.78	15.36	21.75
SR 2 IO	0.25	41.71	0.29	0.00	0.33	12.91	8.18	9.38	10.70
SR 2 OI	0.25	41.71	0.29	0.00	0.33	12.91	8.28	9.38	10.60
SR 3 IO	0.44	41.71	0.28	0.00	0.49	12.90	10.76	6.88	12.05
SR 3 OI	0.44	41.71	0.28	0.00	0.49	12.90	10.74	6.88	12.10
SR 4 IO	0.21	41.71	0.29	0.00	0.29	12.91	3.31	4.52	4.60
SR 4 OI	0.21	41.71	0.29	0.00	0.29	12.91	3.29	4.52	4.61
MAX	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	1.42	200.00	1.00	48.24	2.18	39.09	77.53	54.51	118.84
SR 1 OI	1.43	200.00	1.00	48.38	2.18	39.09	77.71	54.51	118.79
SR 2 IO	1.42	200.00	1.00	46.55	1.95	39.09	46.01	32.49	63.37
SR 2 OI	1.46	200.00	1.00	48.24	1.94	39.09	47.30	32.49	63.02
SR 3 IO	2.15	200.00	1.00	47.77	3.20	39.09	52.73	24.49	78.32
SR 3 OI	2.12	200.00	1.00	46.55	3.20	39.09	52.03	24.49	78.50
SR 4 IO	1.31	200.00	1.00	48.16	1.54	39.09	20.57	15.67	24.09
SR 4 OI	1.30	200.00	1.00	47.77	1.54	39.09	20.43	15.67	24.13
MIN	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.00	56.00	0.02	48.24	0.60	13.27	0.01	1.09	32.92
SR 1 OI	0.00	56.00	0.02	48.38	0.60	13.27	0.04	1.09	32.91
SR 2 IO	0.01	56.00	0.02	46.55	0.37	13.27	0.29	0.65	12.08

SR 2 OI	0.01	56.00	0.02	48.24	0.37	13.27	0.30	0.65	12.05
SR 3 IO	0.00	56.00	0.02	47.77	0.91	13.27	0.02	0.49	22.20
SR 3 OI	0.00	56.00	0.02	46.55	0.91	13.27	0.01	0.49	22.21
SR 4 IO	0.03	56.00	0.02	48.16	0.13	13.27	0.51	0.31	2.08
SR 4 OI	0.03	56.00	0.02	47.77	0.13	13.27	0.51	0.31	2.08

Table C5. Results from June 2015 mass balance using Sulfate.

	Sulfate								
AVG	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.02	28.50	0.51	1.33	1.69	0.89	1.33	27.80	76.43
SR 1 OI	0.02	28.50	0.51	1.26	1.69	0.89	1.24	27.80	76.53
SR 2 IO	0.05	28.50	0.51	1.40	1.47	0.89	1.54	16.57	47.68
SR 2 OI	0.05	28.50	0.51	1.33	1.47	0.89	1.48	16.57	47.73
SR 3 IO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 3 OI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 4 IO	0.34	30.32	0.53	2.44	0.81	3.74	5.31	8.25	12.73
SR 4 OI	0.32	30.08	0.51	0.97	0.81	3.55	5.07	7.93	12.66
STDDEV	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.02	12.44	0.29	0.00	0.28	0.00	0.95	15.73	15.42
SR 1 OI	0.02	12.44	0.29	0.00	0.28	0.00	0.87	15.73	15.47
SR 2 IO	0.03	12.44	0.29	0.00	0.28	0.00	1.04	9.38	9.20
SR 2 OI	0.03	12.44	0.29	0.00	0.28	0.00	0.99	9.38	9.23
SR 3 IO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 3 OI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 4 IO	0.24	11.46	0.29	0.00	0.37	2.77	3.80	4.49	5.77
SR 4 OI	0.24	11.62	0.28	0.00	0.35	2.70	3.73	4.34	5.56
MAX	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.12	50.00	1.00	1.33	2.19	0.89	6.41	54.51	119.35
SR 1 OI	0.11	50.00	1.00	1.26	2.19	0.89	5.78	54.51	119.43
SR 2 IO	0.20	50.00	1.00	1.40	1.98	0.89	6.51	32.49	64.32
SR 2 OI	0.19	50.00	1.00	1.33	1.98	0.89	6.13	32.49	64.37
SR 3 IO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 3 OI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 4 IO	1.61	50.00	1.00	2.44	1.61	7.49	25.23	15.67	25.26
SR 4 OI	1.61	50.00	1.00	0.97	1.49	7.49	25.17	15.67	23.27
MIN	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.01	7.00	0.02	1.33	1.18	0.89	0.32	1.09	64.17
SR 1 OI	0.01	7.00	0.02	1.26	1.18	0.89	0.32	1.09	64.18

SR 2 IO	0.01	7.00	0.02	1.40	0.91	0.89	0.48	0.65	29.44
SR 2 OI	0.01	7.00	0.02	1.33	0.91	0.89	0.48	0.65	29.45
SR 3 IO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 3 OI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SR 4 IO	0.01	7.90	0.02	2.44	0.00	0.89	0.21	0.31	0.00
SR 4 OI	0.00	7.00	0.02	0.97	0.00	0.89	0.00	0.31	0.01

Table C6. Results from August 2015 mass balance using Sodium.

	Sodium								
AVG	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.01	26.55	0.23	1.37	0.14	0.67	1.88	42.96	26.82
SR 1 OI	0.01	26.53	0.23	1.35	0.14	0.64	1.89	43.45	27.31
SR 2 IO	0.12	24.26	0.30	2.29	0.91	0.88	25.93	67.33	176.57
SR 2 OI	0.08	24.99	0.28	1.37	0.92	0.87	18.69	62.08	178.55
SR 3 IO	0.05	26.67	0.55	2.42	0.36	1.14	3.88	46.42	30.45
SR 3 OI	0.04	26.63	0.56	2.29	0.37	1.07	3.65	47.15	31.41
SR 4 IO	0.09	26.53	0.46	2.62	0.68	1.30	7.62	39.67	58.67
SR 4 OI	0.09	26.52	0.47	2.42	0.69	1.16	7.72	40.19	59.09
SR 5 IO	0.05	26.73	0.49	2.69	0.42	1.44	3.58	33.16	28.25
SR 5 OI	0.05	26.72	0.48	2.62	0.40	1.32	3.69	32.34	27.32
SR 6 IO	0.09	26.50	0.51	2.55	0.92	0.92	4.88	26.55	49.63
SR 6 OI	0.10	26.50	0.51	2.69	0.92	0.92	5.13	26.55	49.38
SR 7 IO	0.16	26.80	0.51	2.95	1.08	1.58	6.44	20.79	44.09
SR 7 OI	0.15	26.72	0.51	2.55	1.10	1.58	5.95	20.80	44.59
STDDEV	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.01	13.57	0.12	0.00	0.11	0.65	2.86	21.96	20.58
SR 1 OI	0.01	13.58	0.12	0.00	0.11	0.64	2.81	22.27	20.92
SR 2 IO	0.16	14.08	0.19	0.00	0.16	0.58	34.78	42.80	36.48
SR 2 OI	0.12	13.98	0.17	0.00	0.16	0.58	25.74	38.13	35.02
SR 3 IO	0.07	13.51	0.25	0.00	0.24	0.83	5.62	21.63	19.98
SR 3 OI	0.06	13.53	0.26	0.00	0.24	0.76	5.21	21.77	20.27
SR 4 IO	0.12	13.58	0.29	0.00	0.27	0.94	10.62	24.59	23.34
SR 4 OI	0.12	13.58	0.30	0.00	0.28	0.85	10.12	25.54	24.34
SR 5 IO	0.08	13.48	0.27	0.00	0.25	1.00	5.70	18.36	17.02
SR 5 OI	0.08	13.48	0.28	0.00	0.25	0.95	5.62	18.84	17.27
SR 6 IO	0.12	13.60	0.29	0.00	0.28	0.58	6.13	15.03	14.64
SR 6 OI	0.12	13.60	0.29	0.00	0.28	0.58	6.44	15.03	14.63
SR 7 IO	0.20	13.43	0.29	0.00	0.32	1.05	7.95	11.74	13.20
SR 7 OI	0.19	13.47	0.29	0.00	0.33	1.05	7.69	11.74	13.30

MAX	Qmatrix	Cmatrix	Qloss	Closs	Qkarst	Ckarst	%Qmatrix	%Qloss	%Qkarst
SR 1 IO	0.15	50.00	0.44	1.37	0.36	2.90	28.04	83.97	68.21
SR 1 OI	0.14	50.00	0.44	1.35	0.36	2.90	27.25	83.97	68.25
SR 2 IO	1.17	50.00	1.00	2.30	1.18	1.50	261.04	222.57	262.03
SR 2 OI	0.87	50.00	1.00	1.37	1.18	1.50	193.79	222.57	262.02
SR 3 IO	0.71	50.00	1.00	2.42	0.84	2.90	60.41	84.94	71.28
SR 3 OI	0.67	50.00	1.00	2.30	0.84	2.90	56.51	84.94	71.50
SR 4 IO	1.21	50.00	1.00	2.62	1.27	2.90	103.94	86.21	109.83
SR 4 OI	1.13	50.00	1.00	2.42	1.28	2.90	97.52	86.21	110.18
SR 5 IO	0.92	50.00	1.00	2.69	0.95	2.90	62.77	68.08	64.91
SR 5 OI	0.89	50.00	1.00	2.62	0.95	2.90	60.85	68.08	65.01
SR 6 IO	1.16	50.00	1.00	2.55	1.48	1.50	60.54	52.06	77.04
SR 6 OI	1.21	50.00	1.00	2.69	1.48	1.50	63.24	52.06	76.89
SR 7 IO	1.71	50.00	1.00	2.96	1.71	2.90	69.39	40.68	69.74
SR 7 OI	1.68	50.00	1.00	2.55	1.72	2.90	68.51	40.68	70.09
MIN	Qmatrix	Cmatrix	Qloss	Closs	Qkarst	Ckarst	%Qmatrix	%Qloss	%Qkarst
SR 1 IO	0.00	3.00	0.08	1.37	0.00	0.34	0.01	15.27	0.02
SR 1 OI	0.00	3.00	0.08	1.35	0.00	0.34	0.01	15.27	0.01
SR 2 IO	0.01	3.00	0.02	2.30	0.25	0.34	2.10	4.45	55.13
SR 2 OI	0.01	3.00	0.02	1.37	0.25	0.34	1.76	4.45	56.67
SR 3 IO	0.00	3.00	0.16	2.42	0.00	0.34	0.01	13.59	0.01
SR 3 OI	0.00	3.00	0.16	2.30	0.00	0.34	0.02	13.59	0.01
SR 4 IO	0.00	3.00	0.02	2.62	0.00	0.34	0.01	1.72	0.15
SR 4 OI	0.00	3.00	0.02	2.42	0.00	0.34	0.01	1.72	0.06
SR 5 IO	0.00	3.00	0.04	2.69	0.00	0.34	0.00	2.72	0.01
SR 5 OI	0.00	3.00	0.04	2.62	0.00	0.34	0.01	2.72	0.00
SR 6 IO	0.01	3.00	0.02	2.55	0.18	0.34	0.34	1.04	9.35
SR 6 OI	0.01	3.00	0.02	2.69	0.18	0.34	0.34	1.04	9.30
SR 7 IO	0.02	3.40	0.02	2.96	0.00	0.34	0.63	0.81	0.01
SR 7 OI	0.01	3.20	0.02	2.55	0.00	0.34	0.33	0.81	0.07

Table C7. Results from August 2015 mass balance using Chloride.

	Chloride								
AVG	Qmatrix	Cmatrix	Qloss	Closs	Qkarst	Ckarst	%Qmatrix	%Qloss	%Qkarst
SR 1 IO	0.00	22.50	0.29	1.10	0.21	0.78	0.65	55.34	40.44
SR 1 OI	0.00	22.50	0.28	1.13	0.20	0.78	0.71	53.44	38.47
SR 2 IO	0.10	21.06	0.30	2.65	0.92	1.26	22.86	66.58	178.89
SR 2 OI	0.06	21.82	0.26	1.10	0.92	1.26	13.30	57.83	179.70
SR 3 IO	0.07	22.89	0.56	2.91	0.36	1.57	5.65	47.99	30.25
SR 3 OI	0.06	22.82	0.57	2.65	0.37	1.50	4.91	48.34	31.34

SR 4 IO	0.09	22.50	0.51	2.96	0.72	1.30	8.12	43.97	62.46
SR 4 OI	0.09	22.50	0.51	2.91	0.73	1.30	7.97	43.97	62.61
SR 5 IO	0.08	22.86	0.50	3.06	0.41	1.54	5.41	34.32	27.59
SR 5 OI	0.08	22.84	0.50	2.96	0.41	1.54	5.18	34.29	27.79
SR 6 IO	0.10	22.50	0.51	2.95	0.92	1.30	5.20	26.55	49.31
SR 6 OI	0.10	22.50	0.51	3.06	0.91	1.30	5.40	26.55	49.11
SR 7 IO	0.20	22.50	0.51	3.29	1.05	1.30	7.96	20.75	42.53
SR 7 OI	0.18	22.50	0.51	2.95	1.06	1.30	7.48	20.75	43.01
STDDEV	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.00	10.13	0.09	0.00	0.09	0.00	0.63	17.60	17.24
SR 1 OI	0.00	10.13	0.10	0.00	0.10	0.00	0.72	18.70	18.29
SR 2 IO	0.11	10.40	0.18	0.00	0.15	0.52	23.60	40.89	33.62
SR 2 OI	0.06	10.26	0.15	0.00	0.15	0.52	13.75	33.34	33.07
SR 3 IO	0.06	10.02	0.25	0.00	0.23	1.14	5.43	21.42	19.48
SR 3 OI	0.05	10.04	0.25	0.00	0.23	1.01	4.67	21.41	19.79
SR 4 IO	0.09	10.13	0.29	0.00	0.27	0.52	7.35	24.88	23.16
SR 4 OI	0.08	10.13	0.29	0.00	0.27	0.52	7.21	24.88	23.21
SR 5 IO	0.08	10.02	0.29	0.00	0.26	1.09	5.22	19.59	17.71
SR 5 OI	0.07	10.03	0.29	0.00	0.26	1.09	4.99	19.60	17.81
SR 6 IO	0.09	10.13	0.29	0.00	0.27	0.52	4.75	15.03	14.10
SR 6 OI	0.09	10.13	0.29	0.00	0.27	0.52	4.92	15.03	14.04
SR 7 IO	0.16	10.13	0.29	0.00	0.29	0.52	6.42	11.74	11.94
SR 7 OI	0.15	10.13	0.29	0.00	0.29	0.52	6.00	11.74	11.99
MAX	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.02	40.00	0.44	1.10	0.36	0.78	4.58	83.97	69.22
SR 1 OI	0.03	40.00	0.44	1.13	0.36	0.78	5.17	83.97	69.16
SR 2 IO	0.73	40.00	1.00	2.65	1.18	1.82	163.22	222.57	262.03
SR 2 OI	0.35	40.00	0.80	1.10	1.18	1.82	78.10	178.05	262.02
SR 3 IO	0.52	40.00	1.00	2.91	0.82	5.39	43.76	84.94	70.00
SR 3 OI	0.45	40.00	1.00	2.65	0.83	5.39	38.53	84.94	70.58
SR 4 IO	0.69	40.00	1.00	2.96	1.27	1.82	59.47	86.21	109.33
SR 4 OI	0.68	40.00	1.00	2.91	1.27	1.82	58.45	86.21	109.44
SR 5 IO	0.62	40.00	1.00	3.06	0.94	5.39	41.98	68.08	63.93
SR 5 OI	0.59	40.00	1.00	2.96	0.94	5.39	40.37	68.08	64.11
SR 6 IO	0.73	40.00	1.00	2.95	1.47	1.82	38.23	52.06	76.39
SR 6 OI	0.76	40.00	1.00	3.06	1.46	1.82	39.59	52.06	76.24
SR 7 IO	1.14	40.00	1.00	3.29	1.65	1.82	46.32	40.68	67.22
SR 7 OI	1.06	40.00	1.00	2.95	1.66	1.82	43.04	40.68	67.58

MIN	Qmatrix	Cmatrix	Qloss	Closs	Qkarst	Ckarst	%Qmatrix	%Qloss	%Qkarst
SR 1 IO	0.00	5.00	0.14	1.10	0.06	0.78	0.03	26.72	12.23
SR 1 OI	0.00	5.00	0.12	1.13	0.04	0.78	0.01	22.90	8.54
SR 2 IO	0.01	5.00	0.02	2.65	0.45	0.78	2.84	4.45	99.11
SR 2 OI	0.00	5.00	0.02	1.10	0.45	0.78	0.90	4.45	100.75
SR 3 IO	0.00	5.00	0.16	2.91	0.00	0.78	0.01	13.59	0.00
SR 3 OI	0.00	5.00	0.16	2.65	0.00	0.78	0.10	13.59	0.00
SR 4 IO	0.01	5.00	0.02	2.96	0.15	0.78	0.98	1.72	12.52
SR 4 OI	0.01	5.00	0.02	2.91	0.15	0.78	0.98	1.72	12.54
SR 5 IO	0.00	5.00	0.04	3.06	0.00	0.78	0.08	2.72	0.00
SR 5 OI	0.00	5.00	0.04	2.96	0.00	0.78	0.05	2.72	0.00
SR 6 IO	0.01	5.00	0.02	2.95	0.30	0.78	0.58	1.04	15.46
SR 6 OI	0.01	5.00	0.02	3.06	0.30	0.78	0.58	1.04	15.43
SR 7 IO	0.04	5.00	0.02	3.29	0.20	0.78	1.67	0.81	7.95
SR 7 OI	0.04	5.00	0.02	2.95	0.20	0.78	1.66	0.81	8.02

Table C8. Results from August 2015 mass balance using Magnesium.

	Magnesium								
AVG	Qmatrix	Cmatrix	Qloss	Closs	Qkarst	Ckarst	%Qmatrix	%Qloss	%Qkarst
SR 1 IO	0.02	109.50	0.29	14.36	0.20	6.86	3.69	56.11	38.16
SR 1 OI	0.02	109.50	0.29	14.50	0.19	7.30	3.59	54.87	37.02
SR 2 IO	0.20	98.82	0.36	15.58	0.89	2.93	44.60	80.79	171.35
SR 2 OI	0.20	98.40	0.35	14.36	0.87	2.26	45.46	78.81	168.51
SR 3 IO	0.06	109.87	0.56	16.45	0.37	8.53	4.81	47.94	31.04
SR 3 OI	0.05	109.62	0.57	15.59	0.38	8.28	4.21	48.52	32.23
SR 4 IO	0.11	109.50	0.51	16.76	0.71	8.01	9.63	43.97	60.95
SR 4 OI	0.11	109.50	0.51	16.45	0.71	8.01	9.40	43.97	61.18
SR 5 IO	0.04	109.50	0.72	13.71	0.66	2.26	2.99	49.02	44.70
SR 5 OI	0.07	109.50	0.68	16.76	0.59	2.26	4.50	46.30	40.47
SR 6 IO	0.15	109.74	0.48	15.38	0.84	8.99	7.63	24.84	45.17
SR 6 OI	0.14	109.66	0.49	13.71	0.86	8.68	7.14	25.29	46.11
SR 7 IO	0.20	111.50	0.51	17.74	1.05	11.95	7.94	20.83	42.63
SR 7 OI	0.18	111.06	0.51	15.38	1.06	11.90	7.27	20.72	43.19
STDDEV	Qmatrix	Cmatrix	Qloss	Closs	Qkarst	Ckarst	%Qmatrix	%Qloss	%Qkarst
SR 1 IO	0.03	52.40	0.10	0.00	0.09	5.64	5.65	18.34	17.89
SR 1 OI	0.03	52.40	0.10	0.00	0.09	5.71	5.60	18.40	17.73
SR 2 IO	0.20	53.51	0.22	0.00	0.19	2.69	44.22	48.87	42.94
SR 2 OI	0.19	53.66	0.22	0.00	0.18	0.00	42.34	49.60	40.90
SR 3 IO	0.08	52.20	0.25	0.00	0.23	6.12	6.65	21.65	19.86
SR 3 OI	0.07	52.33	0.25	0.00	0.23	5.95	6.10	21.46	19.90

SR 4 IO	0.13	52.40	0.29	0.00	0.28	5.76	11.48	24.88	24.31
SR 4 OI	0.13	52.40	0.29	0.00	0.28	5.76	11.27	24.88	24.34
SR 5 IO	0.05	52.40	0.17	0.00	0.15	0.00	3.30	11.39	10.00
SR 5 OI	0.07	52.40	0.19	0.00	0.16	0.00	4.86	12.97	11.18
SR 6 IO	0.17	52.26	0.30	0.00	0.30	6.40	8.85	15.55	15.79
SR 6 OI	0.16	52.30	0.30	0.00	0.31	6.22	8.23	15.52	16.03
SR 7 IO	0.22	51.24	0.29	0.00	0.34	7.28	8.97	11.73	13.85
SR 7 OI	0.22	51.51	0.29	0.00	0.34	7.28	8.76	11.66	13.96
MAX	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.26	200.00	0.44	14.36	0.36	13.77	49.49	83.97	69.57
SR 1 OI	0.26	200.00	0.44	14.50	0.36	13.77	50.23	83.97	69.51
SR 2 IO	1.17	200.00	1.00	15.59	1.18	13.77	260.20	222.57	262.01
SR 2 OI	1.18	200.00	1.00	14.36	1.18	2.26	261.56	222.57	262.01
SR 3 IO	0.74	200.00	1.00	16.45	0.84	19.82	63.19	84.94	71.68
SR 3 OI	0.69	200.00	1.00	15.59	0.85	19.82	58.82	84.94	72.07
SR 4 IO	1.15	200.00	1.00	16.76	1.29	13.77	99.56	86.21	110.85
SR 4 OI	1.14	200.00	1.00	16.45	1.29	13.77	97.97	86.21	110.99
SR 5 IO	0.38	200.00	1.00	13.71	0.95	2.26	26.09	68.08	64.55
SR 5 OI	0.57	200.00	1.00	16.76	0.93	2.26	38.50	68.08	63.50
SR 6 IO	1.37	200.00	1.00	15.38	1.48	19.82	71.12	52.06	76.94
SR 6 OI	1.27	200.00	1.00	13.71	1.49	19.82	65.91	52.06	77.40
SR 7 IO	1.70	200.00	1.00	17.74	1.72	19.82	69.11	40.68	69.91
SR 7 OI	1.71	200.00	1.00	15.38	1.71	19.82	69.53	40.68	69.61
MIN	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.00	19.00	0.10	14.36	0.01	2.26	0.01	19.08	2.22
SR 1 OI	0.00	19.00	0.10	14.50	0.01	2.26	0.01	19.08	2.06
SR 2 IO	0.00	19.00	0.02	15.59	0.28	2.26	0.00	4.45	61.39
SR 2 OI	0.04	19.00	0.02	14.36	0.28	2.26	8.80	4.45	61.71
SR 3 IO	0.00	19.00	0.16	16.45	0.00	2.26	0.01	13.59	0.02
SR 3 OI	0.00	19.00	0.16	15.59	0.00	2.26	0.00	13.59	0.01
SR 4 IO	0.01	19.00	0.02	16.76	0.02	2.26	0.62	1.72	1.95
SR 4 OI	0.01	19.00	0.02	16.45	0.02	2.26	0.62	1.72	1.98
SR 5 IO	0.00	19.00	0.44	13.71	0.42	2.26	0.00	29.96	28.61
SR 5 OI	0.00	19.00	0.36	16.76	0.33	2.26	0.06	24.51	22.42
SR 6 IO	0.00	19.00	0.02	15.38	0.00	2.26	0.01	1.04	0.06
SR 6 OI	0.00	19.00	0.02	13.71	0.00	2.26	0.03	1.04	0.03
SR 7 IO	0.01	21.50	0.02	17.74	0.00	2.26	0.52	0.81	0.01
SR 7 OI	0.00	19.00	0.02	15.38	0.00	2.26	0.00	0.81	0.00

Table C9. Results from August 2015 mass balance using Calcium.

	Calcium								
AVG	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.05	128.43	0.26	49.58	0.13	26.90	9.55	48.95	25.15
SR 1 OI	0.05	128.34	0.26	49.39	0.13	26.91	9.42	48.91	25.23
SR 2 IO	0.32	122.15	0.42	51.89	0.82	24.02	71.34	92.54	156.36
SR 2 OI	0.31	122.06	0.41	49.58	0.82	23.82	68.80	91.06	157.43
SR 3 IO	0.12	128.00	0.59	51.45	0.32	25.87	10.61	50.09	27.40
SR 3 OI	0.13	128.00	0.58	51.89	0.32	26.03	10.77	49.68	26.83
SR 4 IO	0.22	128.00	0.51	50.69	0.60	26.18	18.99	43.97	51.59
SR 4 OI	0.23	128.00	0.51	51.45	0.59	26.18	19.43	43.97	51.16
SR 5 IO	0.13	128.00	0.65	46.52	0.50	15.11	8.52	43.96	34.11
SR 5 OI	0.12	128.00	0.68	50.69	0.54	21.88	7.99	46.07	36.76
SR 6 IO	0.31	128.06	0.50	48.88	0.69	27.06	16.19	25.86	37.62
SR 6 OI	0.30	128.04	0.50	46.52	0.71	26.77	15.55	26.07	38.48
SR 7 IO	0.40	128.00	0.51	50.68	0.84	26.18	16.14	20.75	34.35
SR 7 OI	0.38	128.00	0.51	48.88	0.86	26.18	15.65	20.75	34.84
STDDEV	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.05	41.51	0.11	0.00	0.09	13.56	9.25	21.24	17.14
SR 1 OI	0.05	41.54	0.11	0.00	0.09	13.57	9.19	21.26	17.18
SR 2 IO	0.24	41.51	0.26	0.00	0.21	12.73	53.12	56.96	47.53
SR 2 OI	0.23	41.60	0.25	0.00	0.21	12.69	52.26	56.43	47.18
SR 3 IO	0.12	41.71	0.24	0.00	0.20	12.91	9.90	20.63	16.58
SR 3 OI	0.12	41.71	0.25	0.00	0.20	12.91	10.07	20.85	16.63
SR 4 IO	0.17	41.71	0.29	0.00	0.26	12.91	15.05	24.88	22.26
SR 4 OI	0.18	41.71	0.29	0.00	0.26	12.91	15.32	24.88	22.16
SR 5 IO	0.10	41.72	0.24	0.00	0.20	6.65	7.13	16.06	13.75
SR 5 OI	0.11	41.71	0.22	0.00	0.21	12.17	7.81	15.05	14.24
SR 6 IO	0.22	41.68	0.30	0.00	0.29	13.70	11.48	15.36	15.20
SR 6 OI	0.21	41.69	0.29	0.00	0.30	13.45	10.94	15.27	15.37
SR 7 IO	0.26	41.71	0.29	0.00	0.32	12.91	10.67	11.74	13.18
SR 7 OI	0.26	41.71	0.29	0.00	0.32	12.91	10.38	11.74	13.19
MAX	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.31	200.00	0.44	49.58	0.34	56.50	59.67	83.97	65.05
SR 1 OI	0.31	200.00	0.44	49.39	0.34	56.50	59.31	83.97	65.15
SR 2 IO	1.18	200.00	1.00	51.89	1.18	39.09	261.98	222.57	262.03
SR 2 OI	1.18	200.00	1.00	49.58	1.18	39.09	261.96	222.57	262.01
SR 3 IO	0.76	200.00	1.00	51.45	0.79	39.09	64.13	84.94	67.51
SR 3 OI	0.77	200.00	1.00	51.89	0.79	39.09	65.02	84.94	67.28

SR 4 IO	1.13	200.00	1.00	50.69	1.22	39.09	97.04	86.21	105.16
SR 4 OI	1.14	200.00	1.00	51.45	1.22	39.09	98.57	86.21	104.76
SR 5 IO	0.60	200.00	1.00	46.52	0.98	39.09	41.02	68.08	66.57
SR 5 OI	0.70	200.00	1.00	50.69	0.95	39.09	47.67	68.08	64.81
SR 6 IO	1.36	200.00	1.00	48.88	1.39	56.50	70.68	52.06	72.30
SR 6 OI	1.30	200.00	1.00	46.52	1.40	56.50	67.81	52.06	73.07
SR 7 IO	1.60	200.00	1.00	50.68	1.58	39.09	65.00	40.68	64.46
SR 7 OI	1.56	200.00	1.00	48.88	1.60	39.09	63.29	40.68	64.92
MIN	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.00	56.00	0.08	49.58	0.00	13.27	0.08	15.27	0.00
SR 1 OI	0.00	56.00	0.08	49.39	0.00	13.27	0.06	15.27	0.01
SR 2 IO	0.03	56.00	0.02	51.89	0.20	13.27	5.69	4.45	44.14
SR 2 OI	0.03	56.00	0.02	49.58	0.20	13.27	5.62	4.45	44.39
SR 3 IO	0.00	56.00	0.16	51.45	0.01	13.27	0.09	13.59	1.12
SR 3 OI	0.00	56.00	0.16	51.89	0.01	13.27	0.03	13.59	0.97
SR 4 IO	0.02	56.00	0.02	50.69	0.06	13.27	1.57	1.72	5.29
SR 4 OI	0.02	56.00	0.02	51.45	0.06	13.27	1.58	1.72	5.26
SR 5 IO	0.00	56.00	0.24	46.52	0.21	13.27	0.06	16.34	14.26
SR 5 OI	0.00	56.00	0.22	50.69	0.18	13.27	0.08	14.98	12.49
SR 6 IO	0.00	56.00	0.02	48.88	0.00	13.27	0.00	1.04	0.13
SR 6 OI	0.00	56.00	0.02	46.52	0.00	13.27	0.03	1.04	0.04
SR 7 IO	0.08	56.00	0.02	50.68	0.01	13.27	3.09	0.81	0.45
SR 7 OI	0.08	56.00	0.02	48.88	0.01	13.27	3.08	0.81	0.49

Table C10. Results from August 2015 mass balance using Sulfate.

	Sulfate								
AVG	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.00	28.50	0.30	1.51	0.22	0.89	0.81	57.25	42.19
SR 1 OI	0.01	28.50	0.29	1.61	0.21	0.89	1.02	55.34	40.07
SR 2 IO	0.02	28.04	0.25	1.57	0.95	0.89	5.26	55.09	184.99
SR 2 OI	0.02	28.08	0.25	1.51	0.95	0.89	5.07	54.92	185.01
SR 3 IO	0.01	28.50	0.70	1.61	0.55	0.89	0.94	59.46	46.43
SR 3 OI	0.01	28.50	0.71	1.57	0.56	0.89	0.86	60.31	47.36
SR 4 IO	0.04	28.50	0.51	1.68	0.78	0.89	3.05	43.97	67.54
SR 4 OI	0.03	28.50	0.51	1.61	0.79	0.89	2.90	43.97	67.69
SR 5 IO	0.03	28.76	0.43	2.14	0.37	1.72	2.30	29.11	25.48
SR 5 OI	0.03	28.75	0.44	1.68	0.39	1.48	1.95	29.68	26.40
SR 6 IO	0.03	28.50	0.51	1.93	0.99	0.89	1.52	26.55	52.99
SR 6 OI	0.03	28.50	0.51	2.14	0.98	0.89	1.79	26.55	52.72
SR 7 IO	0.22	28.50	0.51	3.16	1.02	1.87	9.01	20.75	41.48

SR 7 OI	0.19	28.50	0.51	1.93	1.05	1.87	7.67	20.75	42.82
STDDEV	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.00	12.44	0.09	0.00	0.08	0.00	0.79	16.49	16.01
SR 1 OI	0.01	12.44	0.09	0.00	0.09	0.00	0.99	17.60	17.00
SR 2 IO	0.02	12.56	0.14	0.00	0.13	0.00	3.82	30.63	29.46
SR 2 OI	0.02	12.56	0.14	0.00	0.13	0.00	3.64	30.52	29.47
SR 3 IO	0.01	12.44	0.18	0.00	0.17	0.00	0.88	15.20	14.68
SR 3 OI	0.01	12.44	0.17	0.00	0.17	0.00	0.80	14.70	14.23
SR 4 IO	0.03	12.44	0.29	0.00	0.28	0.00	2.29	24.88	24.02
SR 4 OI	0.02	12.44	0.29	0.00	0.28	0.00	2.15	24.88	24.09
SR 5 IO	0.04	12.35	0.28	0.00	0.26	1.42	2.40	18.80	17.57
SR 5 OI	0.03	12.35	0.29	0.00	0.28	1.27	1.77	19.95	19.06
SR 6 IO	0.03	12.44	0.29	0.00	0.27	0.00	1.34	15.03	14.31
SR 6 OI	0.03	12.44	0.29	0.00	0.27	0.00	1.59	15.03	14.17
SR 7 IO	0.17	12.44	0.29	0.00	0.32	0.98	6.74	11.74	12.87
SR 7 OI	0.14	12.44	0.29	0.00	0.32	0.98	5.84	11.74	13.12
MAX	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.03	50.00	0.44	1.51	0.36	0.89	5.44	83.97	69.04
SR 1 OI	0.04	50.00	0.44	1.61	0.36	0.89	6.81	83.97	68.87
SR 2 IO	0.11	50.00	0.56	1.57	1.18	0.89	24.80	124.64	262.03
SR 2 OI	0.10	50.00	0.54	1.51	1.18	0.89	23.13	120.19	262.02
SR 3 IO	0.07	50.00	1.00	1.61	0.85	0.89	6.19	84.94	72.08
SR 3 OI	0.07	50.00	1.00	1.57	0.85	0.89	5.63	84.94	72.15
SR 4 IO	0.18	50.00	1.00	1.68	1.29	0.89	15.73	86.21	110.87
SR 4 OI	0.17	50.00	1.00	1.61	1.29	0.89	14.75	86.21	110.99
SR 5 IO	0.26	50.00	1.00	2.14	0.95	7.49	17.43	68.08	64.59
SR 5 OI	0.18	50.00	1.00	1.68	0.96	7.49	12.30	68.08	65.22
SR 6 IO	0.18	50.00	1.00	1.93	1.48	0.89	9.45	52.06	77.30
SR 6 OI	0.22	50.00	1.00	2.14	1.48	0.89	11.24	52.06	77.08
SR 7 IO	1.09	50.00	1.00	3.16	1.66	2.85	44.15	40.68	67.63
SR 7 OI	0.88	50.00	1.00	1.93	1.69	2.85	35.96	40.68	68.69
MIN	**Qmatrix**	**Cmatrix**	**Qloss**	**Closs**	**Qkarst**	**Ckarst**	**%Qmatrix**	**%Qloss**	**%Qkarst**
SR 1 IO	0.00	7.00	0.16	1.51	0.09	0.89	0.00	30.53	16.26
SR 1 OI	0.00	7.00	0.14	1.61	0.06	0.89	0.01	26.72	12.40
SR 2 IO	0.01	7.00	0.02	1.57	0.69	0.89	1.42	4.45	154.26
SR 2 OI	0.01	7.00	0.02	1.51	0.69	0.89	1.42	4.45	154.30
SR 3 IO	0.00	7.00	0.40	1.61	0.26	0.89	0.02	33.98	21.71
SR 3 OI	0.00	7.00	0.42	1.57	0.28	0.89	0.02	35.67	23.44

SR 4 IO	0.01	7.00	0.02	1.68	0.27	0.89	0.60	1.72	23.53
SR 4 OI	0.01	7.00	0.02	1.61	0.27	0.89	0.60	1.72	23.55
SR 5 IO	0.00	7.00	0.04	2.14	0.00	0.89	0.02	2.72	0.00
SR 5 OI	0.00	7.00	0.04	1.68	0.00	0.89	0.00	2.72	0.00
SR 6 IO	0.00	7.00	0.02	1.93	0.51	0.89	0.10	1.04	26.69
SR 6 OI	0.00	7.00	0.02	2.14	0.51	0.89	0.10	1.04	26.65
SR 7 IO	0.06	7.00	0.02	3.16	0.03	0.89	2.53	0.81	1.21
SR 7 OI	0.04	7.00	0.02	1.93	0.03	0.89	1.73	0.81	1.37

Biographical Sketch – Hyrum Tennant, Undergraduate, Civil and Environmental Engineering, Utah Water Research Laboratory, Utah State University

Hyrum Tennant is completing a degree in Environmental Engineering at Utah State University (USU). He is an Undergraduate Research Fellow, Undergraduate Research Fellow Ambassador, a member of USU's Honors program, and USU College of Engineering Ambassador. He decided to pursue a career in environmental engineering rather than secondary education after discovering an interest in water resource engineering while working under the mentorship of Dr. Bethany Neilson as a field technician at the Utah Water Research Laboratory during his senior year of high school. Hyrum was able to full fill his desire to teach by working as an undergraduate teaching fellow and teaching assistant during his senior year and by working with local teachers to conduct research project and outreach events with high school and elementary students as part of their classes. As an active participant in the iUTAH project, an interdisciplinary project studying the changing state of water resources in Utah, Hyrum's undergraduate research has focused on developing methods for quantifying groundwater/surface water interactions in mountainous watersheds with others in Dr. Neilson's research group. The research Hyrum has completed has resulted in his co-authorship of two manuscripts and multiple poster and oral presentations at professional conferences. Hyrum's course work at USU fostered an additional interest in wastewater engineering leading to his current role as design team leader for the Water Environment Association of Utah USU chapter. After finishing his undergraduate degree, Hyrum plans to pursue a Master's degree in Civil and Environmental Engineering at USU.

Capstone Project Reflection

My capstone project greatly enriched my educational experience at Utah State University. Through the process of completing my capstone project I was able to work with an excellent faculty mentor, Dr. Neilson, and multiple graduate mentors, have valuable research experiences with in the environmental engineering field, exercise critical thinking skills, interact and work with professors and students in other disciplines, and see the impact of my work at the state and local level.

Working with Dr. Neilson and her team of graduate students shaped who I am today as a researcher and a student. Dr. Neilson encouraged me to learn and investigate things on my own. She also was always giving me additional responsibilities from training new researchers to managing sampling events. Poster and oral presentations were a "requirement" of working in the Neilson Lab. Dr. Neilson always emphasizes the importance of not only just sharing research results but articulating your results and their relevance in a way that a layperson comprehends and appreciates.

As an undergraduate researcher not only did I just collect the data necessary for my capstone project, but I was able to delve deeply into the field of environmental engineering. I was able to set up, maintain and analyze the results from multiple types of equipment and monitoring stations. Because I was a researcher with field experience, I was able to assist and make contributions to other student's projects such as monitoring and managing the impacts of beaver on watersheds and examining the effects of storm water on river water.

Because my project focused on quantifying the groundwater-surface water exchanges in karst mountainous watersheds, something for which no significant body of work has been completed, I was constantly running into problems that required me to develop procedures that where scientifically rigorous. As part of my project I had to figure out how to gauge a river under high flow conditions for which there is no current standard for how to do in mountainous areas. I also had to determine what ions could be used to distinguish the chemical signatures of different contributing flow members to the Logan River. Over coming these challenges took an abundance of trial and error and many hours of reflection on how I could improve my methodology and approach.

My involvement with the iUTAH project allowed me to spend time working with students and professors from every background. As part of the iUTAH sampling events I helped plan and orchestrate I was able to see how my work informed the research and decisions of sociology, hydrology, geology, chemistry, statistics, watershed science, and landscape architecture students and professors.

The research I conducted for my capstone project, which was partially funded by the iUTAH project, has recently been presented to state and local water managers. It has been very gratifying to know the research I conducted is being used to make policy decisions.

My Honors Capstone Project has been a truly rewarding experience. My advice to future Honors Program participants and Undergraduate Research Fellows would be to get involved early and never miss an opportunity to try something new. The most valuable part of the completing a capstone project is the experience you gain solving problems. If you are a good problem solver, it doesn't really matter what you do in the future; you will always be able to come up with solutions to any problem.